Josep Prat
Editor

Next-Generation FTTH Passive Optical Networks

Research towards unlimited bandwidth access

Springer

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Universitat Politecnica Catalunya
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Spain

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Preface

We are all immersed in a barrier-breaking era: the era of the unlimited communication, without geographical frontiers, without time constrains, without external control and, hopefully soon, without capacity limitations; an era of offering tools for human interaction which are most probably more powerful than any tool developed up to now. Before, communication has started more than a century ago with Morse's telegraph and Bell's telephone by copper wires, augmented later with television via coaxial cable. Also wireless communication grew from Marconi's telegraph to mobile telephony in today's versatile handsets. The big boom in bandwidth demand was caused by the exploding growth of the internet in the last decades. Originally (and still so today in many places), internet services are brought to the homes via the twisted-pair telephony network (using digital subscriber line techniques) or via the coaxial cable CATV network (using cable modems). However, it becomes ever harder to support the fast growing capacity demands of the users, as these copper-based technologies are facing their fundamental bandwidth limitations. The answer is, naturally, the optical fibre: fibre close to the final user, either fibre alone avoiding any future bottleneck, or combined with a last, very short, wireless radio or copper cable link. This vision has been assumed by several telecom organizations and companies around the globe in the last few years, and is nowadays seriously considered by most of them.

Optical fibre access can provide an increase of many orders of magnitude of bandwidth compared to the conventional media, thus the required massive investment in this infrastructure will largely pay back as a very profitable social and economic matter. In order to reduce its initial installation and deployment cost, many projects and initiatives have been undertaken, with a key milestone being the recently launched G/E-PON international standards. This has impelled the deployment of fibre-to-the-home (FTTH) widely spread around the world, with several millions of homes-passed in a short time frame. However, the huge-bandwidth optical infrastructures installed today are not fully used at all. It is left for the future that more advanced electro-optical technologies enable more and better use of the optical bandwidth of the transparent passive optical infrastructure. This is the main aim of current worldwide research on optical access.

The advances on this access network segment are multi-fold. Although the main focus lies on the physical layer of the network, all the communication layers

perform in this segment, which is characterized by the huge number of connecting clients demanding services with quite different characteristics, such as bandwidth and Quality of Service. Among these services are (high-definition) TV, fast internet, multimedia gaming, high-quality radio broadcast, with diverse requirements. The unique new dimension which optical fibre possesses in comparison with its copper cable counterparts is its huge bandwidth, spanning across many terahertz of optical frequencies. This huge optical spectrum of the fibre can be exploited with the technology of wavelength division multiplexing (WDM), opening up a sea of virtually unlimited capacity for the user. Many techniques and architectures have been proposed for accessing this capacity. However, there is no clear winner solution for the next-generation FTTH, also due to the cost sensitiveness of this segment. This book aims at presenting different alternatives that can be applied in the next generations of passive optical networks (ngPONs).

The first part of this book is devoted to network architectures, the second to electro-optical devices and techniques, the third to the higher layer issues and the fourth part to techno-economic analysis. We trust that the audience interested in the future broadband access communication technologies will gain some highlight and ideas of the different covered areas when reading this book.

January 2008

Josep Prat, Barcelona
Ton Koonen, Eindhoven

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We would like to acknowledge the contributing efforts of the many co-authors, partners of the Network of Excellence, and the contribution by British Telecom and Nokia Siemens Portugal gathering advances from another key consortium, the FP6 MUSE Integrated Project. Finally, reaching to the completion of the book would not have been possible without the relentless effort by our colleague Bernhard Schrenk in the last weeks.

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Abbreviations

ABR	Available Bit Rate
ADSL	Asymmetric Digital Subscriber Line
AES	Advanced Encryption Standard
AF	Assured Forwarding
AGC	Automatic Gain Control
APC	Angled Physical Contact
APD	Avalanche PhotoDiode
APON	Asynchronous Transfer Mode Passive Optical Network
ASE	Amplified Spontaneous Emission
ASIC	Application-Specific Integrated Circuit
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
ATMR	Asynchronous Transfer Mode Ring
AWG	Arrayed Waveguide Grating
AWGM	Arrayed Waveguide Grating Multiplexing
BE	Best Effort
BER	Bit Error Ratio
BiDi	BiDirectional
BPF	Bandpass Filter
BPON	Broadband Passive Optical Network
BSWSF	Bidirectional Single Wavelength Single Fibre
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
CATV	*Originally*: Community Antenna Television; *now*: Cable Television
CBR	Constant Bit Rate
CHIL	Channel Insertion Loss
CO	Central Office
CoS	Class of Service
CPE	Customer Premises Equipment
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CSO	Composite Second Order
CTB	Composite Triple Beat

CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DBA	Dynamic Bandwidth Allocation
DBR	Distributed Bragg Reflector
DCF	Dispersion Compensation Fibre
DF	Distribution Fibre *or* Distribution Frame
DFB	Distributed FeedBack
DMT	Discrete MultiTone
DPSK	Differential Phase Shift Keying
DSF	Dispersion Shifted Fibre
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Loop Access Multiplexer
DWA	Dynamic Wavelength Assignment
DWDM	Dense Wavelength Division Multiplexing
EAM	ElectroAbsorption Modulator
EATS	Earliest Arrival Time Scheduling
EDF	Erbium Doped Fibre or Earliest Deadline First
EDFA	Erbium Doped Fibre Amplifier
EDWA	Erbium Doped Waveguide Amplifier
EE	Electronic Equalization
EF	Expedited Forwarding
EFM	Ethernet in the First Mile
EML	Externally Modulated Laser
EPON	Ethernet Passive Optical Network
ETDM	Electrical Time Division Multiplexing
ETSI	European Telecommunications Standards Institute
FBG	Fibre Bragg Grating
FDM	Frequency Domain *or* Frequency Division Multiplexing
FEC	Forward Error Correction
FF	Feeder Fibre
FIT	Failure in Time
FM	Frequency Modulation
FO	Fibre-Optic
FOS	Fixed Optical Splitter
FP-IL	Fabry Perot-Injection Locking
FP-LD	Fabry Perot-Laser Diode
FPR	Free Propagation Region
FSAN	Full Service Access Network
FSK	Frequency Shift Keying
FSR	Free Spectral Range
FTTB	Fibre-to-the-Building
FTTC	Fibre-to-the-Cabinet *or* Fibre-to-the-Curb

FTTH	Fibre-to-the-Home
FWHM	Full-Wave, Half-Maximum
GBA	Geographic Bandwidth Allocation
GBE	GigaBit Ethernet
GCSR	Grating-assisted Coupler with Sampled Reflector
GMPLS	Generalized Multi-Protocol Label Switching
GPON	Gigabit Passive Optical Network
GSM	*Originally*: Groupe Spécial Mobile; *now*: Global System for Mobile communications
HDTV	High Definition TeleVision
HDWDM	High-Density Wavelength Division Multiplexing
HFC	Hybrid Fibre Coaxial
HOL	Head Of Line
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IF	Intermediate Frequency
IM	Intensity Modulation
IM-DD	Intensity Modulation-Direct Detection
IML	Integrated-Modulator Laser
IP	Internet Protocol
ITU	International Telecommunication Union
LAN	Local Area Network
LED	Light Emitting Diode
LLID	Logical Link Identifier
LMDS	Local Multipoint Distribution Service
LQ	Longest Queue
LRD	Long Range Dependent
LR-PON	Long Reach-Passive Optical Network
LT	Line Terminal
MAC	Medium Access Control
MAN	Metropolitan Area Network
MAP	Metro Access Point
MPCP	MultiPoint Control Protocol
MDT	Mean Downtime
MEMS	Micro Electro-Mechanical Systems
MH	Maximum Hop
MIMO	Multiple Input Multiple Output
MPCP	MultiPoint Control Protocol
MPLS	Multi-Protocol Label Switching
MSAN	Multi-Service Access Node
MSK	Minimum Shift Keying
MSP	Modified Strict Priority

MTBF	Mean Time Between Failures
MTTFF	Mean Time To First Failure
MTTR	Mean Time To Repair
MUT	Mean Up Time
MUX	Multiplexer
MVDS	Multipoint Video Distribution System
MZM	Mach-Zehnder Modulator
NF	Noise Figure
ngPON	Next Generation Passive Optical Network
NIU	Network Interface Unit
NRZ	Non Return to Zero
NZDSF	Non-Zero Dispersion Shifted Fibre
OA	Optical Amplifier
OADM	Optical Add/Drop Multiplexer
OBS	Optical Burst Switching
OBS-M	Optical Burst Switching-Multiplexer
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OGC	Optical Gain Clamping
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
OPEX	Operating Expenditure
oPLL	Optical Phase-Locked Loop
OPS	Optical Packet Switching
OS	Optical Switch
OSNR	Optical Signal-to-Noise Ratio
oSRR	Optical Signal-to-Rayleigh Backscattering Ratio
OTDM	Optical Time Division Multiplexing
OTDR	Optical Time Domain Reflectometry
OXC	Optical Cross Connect
P2M	Point-to-Multipoint
P2P	Point-to-Point
PB	Power Budget
PCM	Power Converter Module
PCS	Physical Coding Sublayer
PD	PhotoDetector
PIN	Positive Intrinsic Negative *diode*
PMA	Physical Medium Attachment
PMD	Physical Media Dependent
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PRBS	Pseudo-Random Bit Sequence

PSC	Passive Star Coupler
PSK	Phase Shift Keying
PS-PON	Power Splitter-Passive Optical Network
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAP	Radio Access Point
RB	Rayleigh Backscattering
RBD	Reliability Block Diagram
REAM	Reflective ElectroAbsorption Modulator
RF	Radio Frequency
RN	Remote Node
RND	Random
RNI	Remote Node Interface
ROADM	Reconfigurable Optical Add/Drop Multiplexer
ROCE	Return On Capital Expenditure
RoF	Radio-over-Fibre
RP	Raman Pump
RPQ	Rotating Priorities Queues
RR	Round Robin
RSOA	Reflective Semiconductor Optical Amplifier
RTT	Round Trip Time
SAN	Storage Area Network
SCM	SubCarrier Multiplexing
SDH	Synchronous Digital Hierarchy
SG-DBR	Sampled Grating-Distributed Bragg Reflector
SLA	Service Level Agreement
SMF	Single Mode Fibre
SMSR	Side-Mode Suppression Ratio
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SOP	State of Optical Polarization
SP	Service Provider *or* Strict Priority
SRD	Short Range Dependent
TC	Transmission Convergence
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TF	Task Force
TQ	Time Quantum
TVoD	TeleVision on Demand

UBR	Unspecified Bit Rate
UDWDM	Ultra-Dense Wavelength Division Multiplexing
UMTS	Universal Mobile Telecommunications System
UTP	Unshielded Twisted Pair
UWB	Ultra WideBand
VBR	Variable Bit Rate
VCSEL	Vertical Cavity Surface Emitting Laser
VCSOA	Vertical Cavity Semiconductor Optical Amplifiers
VDSL	Very high rate Digital Subscriber Line
VOA	Variable Optical Attenuator
VoIP	Voice over Internet Protocol
VOS	Variable Optical Splitter
WC	Wavelength Converter
WDM	Wavelength Division Multiplexing
WDMA	Wavelength Division Multiple Access
WGR	Wavelength Grating Router
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WIS	Wide area network Interface Sublayer
WLAN	Wireless Local Access Network
WPAN	Wireless Personal Area Network
WROBS	Wavelength Routed Optical Burst Switching
XFP	*10 Gigabit* Small Form-Factor Pluggable *module*
XGM	Cross Gain Modulation
XL-PON	Extra Large Passive Optical Network

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Chapter 1
Introduction

Optical fibre access to the user, the so-called Fibre-to-the-Home (FTTH), is becoming a mature concept and a reality in many regions of the globe, with more than 8 millions homes already connected, in an exponential growth. As it is widely accepted, FTTH is the only future-proof technology that will be able to support the upcoming interactive multimedia services, and nowadays operators are planning to substitute the existing telephone-line-based systems (Asymmetric Digital Subscriber Line ADSL, Plain Old Telephone Service POTS) or cable systems (Cable Television CATV) per optical fibre. First, point-to-point fibre links; recently, the more advanced point-to-multipoint Passive Optical Networks (PON) are being deployed to implement FTTH – currently in Asia and USA mainly. The first generation PONs (Broadband PON, Gigabit PON, Ethernet PON) have been recently standardized, offering symmetrical Gigabit/s bandwidth typically shared among few tens of users.

In future, further generations of PONs will be available (in the same way as we have had multiple generations of Digital Subscriber Line, DSL) and there will be drivers to deploy some of them aiming towards higher capacity, lower cost, newer services and Quality of Service (QoS) diversification.

This document focuses onto discussion of the technical options for next generation PONs (ngPONs) and aims at proposing and analyzing new architectures as well as enabling technologies. True-broadband access (10/100 Mbps) may drive the telecommunications sector again towards relevant positions in terms of social and economic development. If -with the advanced techniques proposed- operators can implement a gradual upgrade-path to their infrastructure from a basic one that is probably already deployed to an all-optical network, the development can be effectively done.

The main focus of the report is on very high-density scalable broadband-for-all access networks, for scenarios where the scalability and the continuous growth of the fibre network is an essential requirement for the operator business plan. This may occur in fibre-limited or saturated areas and also where the long term cost effectiveness drives a green-field deployment. Thus, current approaches like current point-to-point fibre-rich plants or standardized Time Division Multiplexed (TDM) PONs (GPON, EPON) are not extensively dealt within this text, which mainly focuses on longer-term generations of PONs.

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Research activities are focusing on possible extensions of current GPON and EPON since these systems may suffer bandwidth limitations in the future, and they do not make use of the full optical bandwidth. The high initial capital expenditure required in new FTTH deployments compels network designers and operators to assure migration paths that guarantee future full usage of infrastructure investments, avoiding bottlenecks at any demand increase. Thus, the major goal is to reduce the overall access network cost while assuring a remarkable symmetrical bandwidth per user, establishing an optical passive transparent infrastructure over a dense extended-range area, capable of supporting unknown future demands. This is driving the research towards extended, practically-unlimited-bandwidth **next-generation PONs**. The time scale for the migration of current PON systems towards it can be highly variable, perhaps in a 2–8 years timeframe, although driven by the mentioned unpredictable user demands. A wide range of operators and system vendors are aiming their R&D interests towards this field considering this.

Wavelength Division Multiplexing (WDM) technology straightforwardly offers a new dimension for this upgrade. A future implementation of next generation PONs can be only foreseen if new cost-effective techniques and devices are used. WDM access can be pure-WDM-PON or hybrid TDM/WDM-PON; the latter offers a higher level of granularity and scalability, so it constitutes the main research focus (Fig. 1.1). However, there are relevant barriers in the migration towards WDM in FTTH: the increased cost of WDM components in the access field and the availability of technological solutions to guarantee the robust and unlimited usage of the extended PON.

If, with the advanced techniques proposed, operators can realize the possibility to highly scale their infrastructure, from a basic one already deployed, the extended development, in terms of number of served users, bandwidth and distance, can be effectively prompted. The basic scenario of the project is on scalable high-density broadband-for-all access, i.e. environments where the scalability and the continuous growth of the fibre network are an essential requirement for the operator's business plan. This may occur in fibre-limited or saturated areas, and also where the long-term cost-effectiveness validates a green-field deployment. With the extended performances, if PONs can also incorporate resilience and intelligent functionalities of

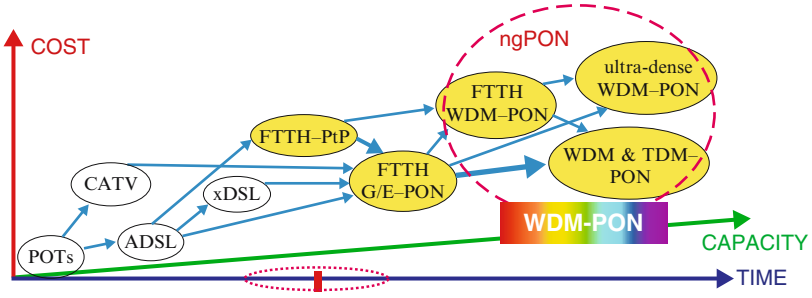

Fig. 1.1 Evolution of access technologies

metropolitan networks, one can envisage an access-metro networks convergence in the long-term, which is becoming a new interesting concept for the integration and simplification of telecommunication networks.

Considering this, the main features that may define a highly scalable new-generation PON may be the following:

- High splitting ratio (>64)
- High speed (>1 Gbps)
- High bandwidth per user (>100 Mbps)
- Bidirectional transmission, symmetrical data rate, single fibre access
- Long reach (>20 km)
- Passive
- Simple upgradeability
- Centralized management
- Dynamic resource allocation
- Basic protection incorporated

Another point to address is that some operators already have a legacy PON problem and how they will evolve from BPON/GPON/GE-PON to ngPON – if the network will be leaning fibre, such that ngPON will need to share fibres with legacy PONs. All those are questions not solved so far. In this case, there will be difficult technical challenges such as wavelength plan discussions. For example, if ngPONs can be deployed on separated fibres to legacy PONs, the design of the ngPON is perhaps easier. It is quite probable that different operators will have different situations.

1.1 Organization of the Document

This book is organized as follows. Chapter 2 is devoted to the optical architectures of PONs, making emphasis on advanced concepts that can accommodate increased bandwidth, higher number of users and provide better utilization of optical resources. Relevant concepts like reconfigurable or wavelength routed PONs and multi-dimension multiplexing schemes are applied. Also, the development of the current Gigabit G/E-PON standards towards next generation PONs with increased bit rate and range is analyzed.

Chapter 3 deals with components for future access: colourless Optical Network Units (ONUs), tuneable lasers and wavelength routers, which are all essential devices for advanced access networks.

In Chapter 4 focuses on transmission techniques for ngPONs: single fibre single wavelength bidirectional transmission, new modulation formats, forward error correction techniques and other strategies to enhance data transmission. These are key enabling techniques for the future growth of PON performance and functionalities.

Chapter 5 presents network protection schemes applied to access networks and Chapter 6 develops traffic studies focused on access networks.

Finally, Chapter 7 deals with the convergence of metro and access infrastructure into a single platform and Chapter 8 justifies, from an economic point of view, the need to deploy advanced topologies in order to achieve a cost effective access solution.

The whole set of issues treated in this document can provide a feasibility basis for relevant performances of new and upgraded optical access networks compared to current solutions, and offers an incentive for continuing R&D towards a cost effective broadband-for-all reality.

Chapter 2
Architecture of Future Access Networks

Carlos Bock, Philippe Chanclou, Jorge M. Finochietto, Gerald Franzl, Marek Hajduczenia, Ton Koonen, Paulo P. Monteiro, Fabio Neri, Josep Prat, and Henrique J. A. da Silva

A key issue to reach a highly scalable Passive Optical Network (PON) with very high splitting ratio is the high multiplexing level required to handle all individual signals (individual data flows) that travel along shared fibres. The available fibre bandwidth and current high-speed electronics allow high splitting ratios together with high bandwidth per user assignments. An objective in a next generation PON (ngPON) is to perform the multiplexing with limited complexity. The possible multiplexing techniques in the key architectures are discussed in this chapter.

2.1 Multiplexing Level

Any of the basic independent dimensions of multiplexing can be used in optical communications, summarized as follows:

- Time domain: Optical and Electrical Time Division Multiplexing (OTDM, ETDM), where each user (Optical Network Unit, ONU) has access to individually assigned time slots. This can be either static or dynamical as in optical packet switching (OPS), providing dynamic bandwidth allocation (DBA) for varying capacity demands. If we consider a bit rate of 10 Gbps for optical channels and an assigned bandwidth per user of 100 Mbps in average, the multiplexing level for active users is in the order of 100.
- Electrical frequency (FDM) domain, also known as subcarrier multiplexing (SCM), for Radio-over-Fibre (RoF), xDSL (Digital Subscriber Line) or others: Each Optical Network Terminal (ONT) has an assigned frequency; all channels are combined at the remote node and demultiplexed at the Optical Line Terminal (OLT). With a similar multiplexing level like TDM, FDM suffers from Signal-to-Noise Ratio (SNR) and non-linearity limitations. This technique allows to offer compatibility with current systems and to minimize complexity in remote antennas of RoF systems.
- Wavelength (optical frequency) domain: Wavelength Division Multiplexing (WDM), with the possible different densities (Coarse-WDM CWDM, Dense-WDM DWDM) and static or dynamic wavelength assignment, offer the highest possibilities. In an access scenario, multiplexing levels between 20 and 100

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wavelengths per fibre can be foreseen. Long term approaches like ultra-dense WDM with homodyne detection are in research.

- State of optical polarization (SOP) domain: This is limited to two orthogonal components; thus, its utilization is per se not attractive in access. If combined with other multiplexing techniques it allows to double the number of channels on a single fibre. However, this option is still in research and requires sophisticated transceivers.
- A special case is code division multiplexing (CDM), as it is not an independent physical domain, i.e. it exploits correlation techniques to open a mathematical multiplexing domain. It can be regarded as an asynchronous way of sharing the time or the frequency depending on the approach (e.g. coherence multiplexing, spread-spectrum), in the electrical or in the optical domain. These systems suffer from SNR limitations and technological complexity that limit the number of users to a fraction of the theoretically possible.

Different multiplexing techniques (dimensions) can be combined. Effectively, if splitting ratios above two orders of magnitude are to be reached in ngPON, we can see from the numbers above that the techniques need to be combined in hybrid multiplexing solutions (Fig. 2.1), thus giving potential for three or four orders of magnitude for capacity splitting.

Hybrid multiplexing (multi-domain) has been investigated in several works on access technologies, with the aim of reaching high resource sharing levels. Many works on that topic can also be found from the Radio Frequency (RF) community on wireless transmission systems trying to either maximally exploit channel capacities, i.e. trying to reach the Shannon limit, or to detect signals below the noise floor.

The combination of TDM and WDM is extremely powerful. A pioneering approach [Bianco99] combined TDM/OPS and dynamic WDM routing in a peer-to-peer switchless network. It had nation-wide potential depending on the number of ports of the N × N wavelength router. It also used tuneable lasers and several wavelength converters to avoid blocking. Another approach, with centralised PON topology has been demonstrated in [Bock05]. It makes use of cyclic properties of a matched Arrayed Waveguide Grating (AWG) and tuneable lasers at the OLT, and reflective ONTs. Already a simple combination of static WDM or CWDM and the current PON standards (Gigabit and Ethernet Passive Optical Network, GPON and

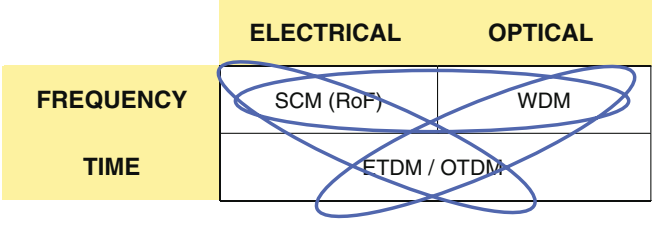

Fig. 2.1 Hybrid multiplexing – combining dimensions

EPON) that, in the last versions, include DBA, constitute an efficient and straightforward solution in the mid term [Bock05].

Currently there is a trend to combine WDM and SCM in optical access networks using radio-frequency carriers. This increases the system flexibility in order to simplify network management issues. For example, several base stations in a wireless system can be fed through a single fibre: each one having its own wavelength in which different users served by a particular base station would be multiplexed by means of SCM. Following that trend, we find an experiment based on optical heterodyne detection in which two 155 Mbps-DPSK (Differential Phase Shift Keying) RF channels at 59.6 and 60 GHz are multiplexed on two optical wavelengths (1549.92 and 1550.12 nm) in the literature [Kuri03].

In a more recent experiment a total of 15 channels were sent through an optical fibre with combined multiplexing of five radio-frequency channels of 155 Mbps in the 18.5 GHz band with 450 MHz spacing, multiplexed over three wavelength channels of 1549.9, 1550.3 and 1550.7 nm [Kaszubowska04a]. In order to increase the spectral efficiency the technique of wavelength interleaving is being investigated. A complete and interesting system analysis of the technique is found in [Kaszubowska04b].

Finally, very recent issues show interest in the WDM/SCM multiplexing approach by proposing performance improvements in the modulation format used [Jung05].

2.2 WDM – Passive Optical Network

Multiplexing in the optical domain, where the parameter used to identify different channels is the wavelength, has enabled an extraordinary increase of the capacity of optical transmission systems in the last decade.

In high-capacity environments, the WDM extension DWDM operates with channel spacing as small as 0.8 or 0.4 nm, at 1–40 Gbps. This technology requires advanced elements (e.g. highly stable wavelength sources, precise optical filtering, cross-channel light-power management) and its application to access networks has been limited up to now.

CWDM is emerging as a robust and economical solution. Typical CWDM spacing is 20 nm (ITU-T G.694.2 grid, International Telecommunication Union) and does not require a temperature control to build sufficiently stable wavelength sources. Consequently, CWDM transceivers with no temperature control, comparably simple directly modulated lasers and quite wide bit rate transparency are typically lower in cost, size, and power consumption than their conventional highly specialised WDM/DWDM counterparts.

2.2.1 Wavelength Allocation Strategies

By introducing multiple wavelengths into a common fibre infrastructure, the capabilities of this infrastructure can be extended into an additional dimension

[Koonen05], [Urban05]. This wavelength dimension may implement independent communication planes between nodes, thus enabling interconnection patterns between nodes that can be asynchronous, can serve different QoS (Quality of Service) requirements and can transport signals with widely differing characteristics (e.g. bit rate). This has some similarity with the enhanced interconnection possibilities of multilayer printed circuit boards, as compared to single layer boards.

The role of this wavelength dimension can be manifold:

- To separate services
- To separate service providers
- To enable traffic rerouting
- To enable higher capacity

Also the assignment of the wavelength channels may follow different scenarios:

- Static allocation
- Semi-static allocation
- Dynamic allocation

Each of the above-mentioned roles may follow one or more of the scenarios. In the following, each of the roles will be considered in more detail.

2.2.1.1 Service Separation

By allocating a wavelength (or a set of wavelengths) for a cohesive set of services, these services may be separated by means of their wavelength. This may be beneficial for treating such a set of services with similar QoS requirements and signal characteristics in a dedicated way. For example, bidirectional multimedia services may have specific requirements for latency and bandwidth, and hosting these in one or more specific wavelength channels with their dedicated routing patterns may help for supporting these requirements. By applying wavelength routing in a point-to-multipoint architecture, a lower split factor may be implemented for services with high bandwidth requirements, whereas other services may get higher split factors.

Separating services on a wavelength basis may also help to realise different tariff structures by the network operator: traffic travelling on the first-priority (e.g. guaranteed congestion-free) wavelength channel may be charged against a higher fee than on lower-priority channels.

2.2.1.2 Service Provider Separation

Wavelength channels may also be dedicated to service providers. They thus get each their virtually independent infrastructure, on which they can guarantee their own basket of services and pertaining QoS. It also enables flexible leasing of network capacity by the network operator, who may assign a certain set of wavelength

channels for a certain region and a certain period to a specific service provider, and charge him for that. By rerouting the wavelength channels the network operator can easily change these leasing conditions. When a user subscribes to a particular service provider, he may get the corresponding wavelength channel(s) and thus transparently the services involved.

In case of several competing service providers in the same region, these providers may thus co-exist on the same network independently.

2.2.1.3 Traffic Rerouting

Using multiple wavelength channels serving different regions, each wavelength channel or set of wavelength channels may feed a certain region. When operating in networks with diversity in fibre links (e.g., in a mesh network in which various fibre paths can be followed to establish a connection between two nodes), wavelength-specific routing actually ties wavelengths to regions. By changing the wavelength routing, this "colouring" can easily be changed. For instance, when a specific fibre link feeding a region fails and the traffic carried through the wavelength channels is disrupted, the traffic provisioning to that region may be quickly restored by steering the wavelength channel(s) via alternative fibre paths.

Also when a link feeding a certain region gets congested and no extra wavelength channels can be added to that link, these extra channels may be routed via alternative fibre links to the same region.

2.2.1.4 Higher Capacity

Adding wavelength channels to a fibre link may also just increase the capacity on the link, by creating several channels in parallel carrying the same type of traffic. This e.g. implies that more of the same services may be offered. To get access to those services, however, the end user needs to be retuned to that wavelength channel.

2.2.2 Dynamic Network Reconfiguration Using Flexible WDM

In the long term vision for access networks, a user should have congestion-free access to virtually unlimited amounts of information which are available to him at any time, anywhere. Actually, in his need for communication the user should not be limited in any way by the communication infrastructure surrounding him. Trends observable in the market which drive this thirst for information are e.g. the personalisation of services, peer-to-peer communication, fast file transfer (e.g. for storage area networks), increasing high-Q video content, roaming with broadband services, etc.

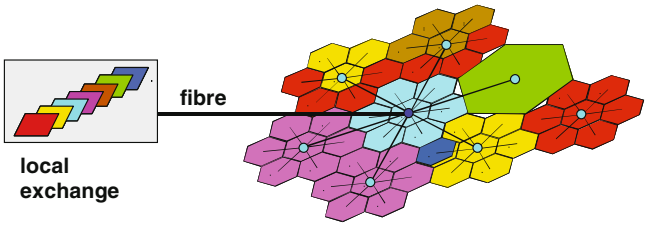

Fig. 2.2 Dynamically routing wavelengths among access network cells for flexible service provisioning

Obviously, this vision can only be realised with an access network infrastructure of which the communication power exceeds any present and foreseeable user communication need. A brute-force solution could be to provide abundant communication power everywhere, no matter whether it is needed at that instant or not. However, this will incur excessive infrastructure costs, which is even a more severe problem in the access network where costs need to be low because of the low per-user network sharing factor. Hence, it is more efficient to build intelligence in the access network, in order to provide an adjustable amount of communication power tailored to the actual instantaneous and temporal user needs. For example, as illustrated in Fig. 2.2, by flexibly assigning communication capacity to city areas, weekly or daily shifts in traffic patterns in a city environment may thus be handled more efficiently, or the quasi-static allocation of certain areas for licensing by service operators.

Flexible capacity allocation can also readily handle suddenly occurring 'hot spots', as may pop up in e.g. highway traffic jams, in airport lounges, or during weekend hours in a shopping mall.

Next, for avoiding the massive capacity over-provisioning of the brute force method, the dynamic reconfiguration will also provide elegant ways for upgrading the network capacity as the user demands grow and for enabling the operator to more efficiently deploy his (scarce) telecommunication resources and thus make a better business profit. Because of the cost critical nature of access networks, the proposed intelligence mechanisms need to be cheap.

Using dynamic optical routing techniques, the aggregate capacity available from a local exchange can be partitioned flexibly among network areas in such a way that their traffic demands are adequately met. This basic approach is illustrated in Fig. 2.2, using multiple wavelength channels for service delivery. Depending on the actual traffic load, a wavelength channel may serve one or more network cells.

2.2.2.1 Static Wavelength Allocation

Statically assigning wavelength channels to end users is comparable to hard-wiring the infrastructure, and thus is functionally similar to today's network situation.

For example, users have subscribed to a particular service provider, who is using a fixed wavelength channel, and the network has fixed means to let the user have access to that wavelength channel (or set of wavelength channels) only. When the user wants to change to another service provider, a technical service operator has to alter the user's wavelength channel selection hardware. This complicates the liberalisation of service provisioning.

2.2.2.2 Semi-Static Wavelength Allocation

When the wavelength selection mechanisms in the network or at the end user are not fixed, but can be changed on a non-frequent basis, this allows rearrangement of the wavelength allocation on a circuit-switched basis. For example, it can support the introduction of new services and/or service providers into targeted regions, by directing the corresponding wavelength channels into that region. It also can support the change of subscription of an end user to services and/or service providers, by changing the wavelength channel(s) to be fed to him.

Such wavelength steering advantageously can be done remotely from the network operator's site. He may command the wavelength routers in the field or control the wavelength-selective tuneable filters at the end user. Thus, he also can facilitate and speed up his service provisioning process, without having to send the technical service operator to the field with the associated costs and administrative overhead. He also can circumvent certain parts of the network, thus bypassing failing links or nodes, or making these network parts accessible for maintenance or upgrading while keeping the rest of the network in-service.

The semi-static wavelength steering may also be used for provisioning capacity in response to slowly changing traffic patterns. For example, the daily shifts of traffic intensity as they typically occur in cities may be taken into account. As illustrated in Fig. 2.3, in the morning most of the traffic demands may come from domestic neighbourhoods, where people want to download the morning news. During office hours, most traffic may be requested by the business park (with more

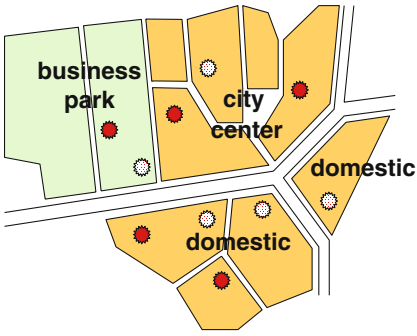

Fig. 2.3 Traffic shifts in urban environment

symmetrical traffic profiles for file transfer) and by the shops in the city centre. And in the evening this traffic demand may shift back again to the domestic neighbourhoods, for online gaming, other internet amusement, etc. These well-predictable traffic demand shifts may be programmed into a semi-static wavelength re-assignment strategy.

2.2.2.3 Fast Dynamic Wavelength Allocation

When the wavelength selection mechanisms can operate fast, they may be able to operate on a per flow basis. For example, assume that a service's packet stream (flow) is carried by a certain wavelength channel, but at a given moment a higher-priority service needs to be transported by that same channel but cannot get sufficient room in it. Then the lower-priority service may be transferred to another wavelength channel and thus setting free sufficient room for the high-priority one. This dynamic allocation may reduce the congestion problem by effectively combining the resources of separated wavelength channels into one common pool of resources, in which by fast wavelength re-assignment every end-user's service can find its share and an autonomous reassignment strategy dynamically optimises resource utilization. It thus increases the efficiency with which the network resources are deployed.

This dynamic allocation enables capacity-on-demand and directs the network resources (the wavelength channels) to those places in the network where the instantaneous traffic load requires them. Obviously, this also requires careful traffic monitoring and control processes on a 'per flow' level and thus a more complicated network management and control system.

2.2.2.4 Introduction Scenarios for Flexible Wavelength Allocation

For the medium term, the most rewarding scenario to implement may be the semi-static wavelength allocation. It significantly enhances the capabilities (i.e. flexibility) of the network operator, without requiring an overly complicated management and control system. It also puts moderate requirements on the tuning speeds of the wavelength selective elements, thus making means of electro-mechanical and thermo-optic tuning suitable candidates.

A combination of the service separation and service provider separation roles seems to be the most eligible in combination with the semi-static allocation. When bidirectional traffic is to be fed via a single fibre to the end user, each communication channel with its downstream and upstream path will require two wavelength channels. To facilitate common routing/filtering, these two channels should be preferably positioned next to each other. Each service provider may then lease a wavelength band from the network operator, containing one or more wavelength pairs in order to provide and deliver one or more sets of services. Wavelength channel allocations may thus look like the example shown in Fig. 2.4.

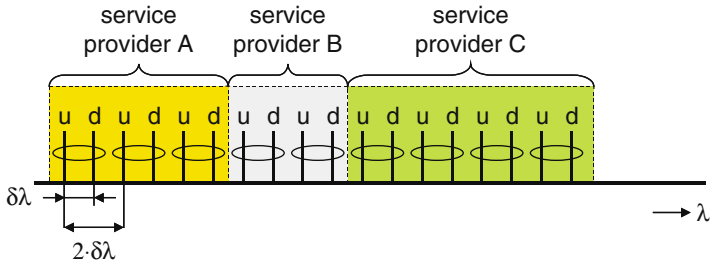

Fig. 2.4 Assigning wavelength bands per service provider and within each band separate wavelength channels for service differentiation (u: upstream channel, d: downstream channel), using a wavelength grid with channel spacing δλ

2.2.3 Static WDM PONs

WDM is a very promising technique to exploit the available bandwidth of optical fibres. However, its application to access is limited because of the cost of conventional WDM optical components.

Dense-WDM systems accommodate channels in the C- and L-bands with a channel spacing from 100 to 25 GHz, defined in the ITU-T G.694.1 grid. Those systems require thermal stabilization to prevent wavelength drifts and very precise control electronics. The price of this equipment is high and its application in an access environment is difficult to justify from the economic point of view.

In order to reduce the cost of optical transceivers and to relax the design criteria of WDM systems, a lower-spec version of WDM was developed, targeted mainly for metropolitan networks but also able to be used for access. The so-called Coarse-WDM does not require thermal stabilization, as the separation between channels is approximately 2.5 THz. Also, the design of multiplexers and de-multiplexers is simpler and the tolerances are higher. ITU-T G.694.2 defines the centre wavelengths and the separation between channels which is 20 nm. With this channel spacing, up to 16 CWDM channels can be transmitted on a single fibre.

As CWDM channels according to ITU-T G.694.2 span the entire wavelength band between 1,310 and 1,610 nm, including the area where OH scattering might occur, the use of OH-free fibres according to ITU-T G.652.C and G.652.D is recommended. Avoiding the critical area reduces the number of applicable wavelength channels to eight, i.e. 1,310 and 1,490–1,610 nm. However, it enables to use CWDM with legacy fibres according to ITU-T G.652 that are readily deployed in the field. Wideband optical amplification as it is widely used with WDM and DWDM to extend optical spans to hundreds of kilometres is not available for CWDM and is therefore limiting the optical links in CWDM systems to several tens of kilometres.

CWDM in access provides interesting solutions to create both, high density and high bandwidth access networks. Basically, there are two approaches: network overlay and service overlay.

2.2.3.1 Network Overlay

The principle of this approach is to multiplex several equal PONs on a single fibre trunk and use two overlayed routing stages to reach the end users. The first stage performs the CWDM routing and the second stage is the classical PON power splitter. Figure 2.5 presents this approach.

This solution extends the number of users served by a single fibre. The multiplying factor is the number of wavelengths so theoretically we can increase the capacity to 16 times the number of users. Practically, there are some restrictions. If we use legacy fibre, the 1,400 and 1,380 nm wavelengths are not used due to water peak losses. Also, if we use a single fibre outside plant, we require upstream and downstream wavelengths, efficiently causing the number of sub networks to be divided by a factor of 2.

The implementation however is very simple: N CWDM interfaces, where N is the number of sub networks and also gives the number of CWDM wavelengths (channels) required, are coupled and transmitted on a single trunk fibre to the first remote node, where each CWDM channel is routed to a secondary tree (sub network). Then, a secondary power-splitting stage distributes the signal among all the ONUs of that network sub segment. Upstream transmission is identical to the classical TDM PON approach. Actually, it is fully compatible except for the transmission wavelength of each sub network. Each sub network has a dedicated upstream wavelength and therefore, ONUs from the same sub network use the same wavelength for upstream transmission. There are several solutions to avoid the ONUs to be different depending on the sub network they are attached to. Broadband sources and spectrum slicing is one of the solutions proposed.

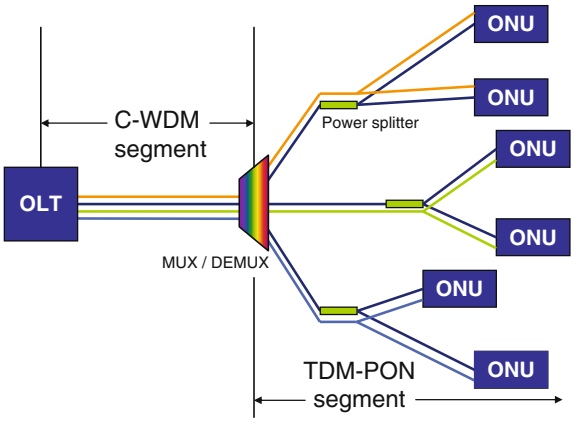

Fig. 2.5 Coarse-WDM network overlay

2.2.3.2 Service Overlay

Another interesting use of CWDM in access is to offer different services on different CWDM channels. In this approach the number of users is defined by the power splitting factor so there is no gain on the number of users that the network serves. However, the network capacity is increased by a factor equal to the number of wavelength used, which enables a corresponding increase in the number of services provided.

The outside plant is identical to the standard PON case, with a single power-splitting stage and the CWDM equipment is located at the OLT and ONUs. Fixed CWDM filters at the ONUs de-multiplex the different services that are delivered. At the same time, different CWDM interfaces at the OLT transmit the different services that are offered.

Many interesting applications use the service overlay model. For example different service providers can use the same network infrastructure owned by a third party and/or different services (video, data, voice, etc.) can be delivered using different wavelengths on subscription basis depending on the end user preferences, to name the most common (Fig. 2.6).

Furthermore, this approach is very flexible as to activate a new service just requires the installation of a CWDM filter and a photo-receiver at the ONU of the subscriber.

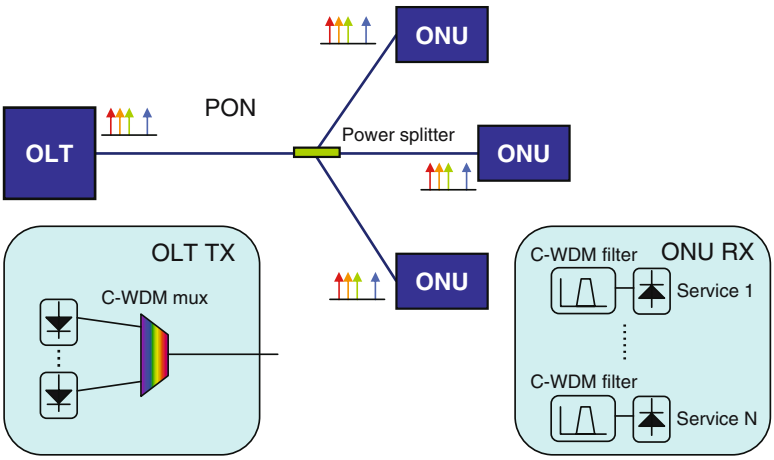

Fig. 2.6 Typical implementation of service overlay

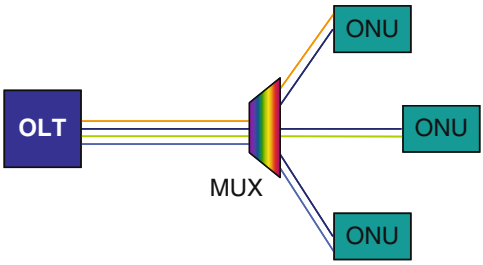

Fig. 2.7 WDM PON

2.2.4 Wavelength Routed PON

WDM PONs are based on multiplexing of users on a shared fibre infrastructure using a specific wavelength for each terminal. This technique creates a virtual point-to-point connection that allows full duplex transmission with optical bit rates independently of the traffic caused by other users (Fig. 2.7).

The main drawback of WDM PONs is the high cost of implementation and the limited number of wavelengths available, i.e. the low splitting factor. First of all, at the OLT there is the need to install one laser for each ONU connected to the network, increasing the number of optical equipment at the OLT side. Also, in the outside plant a wavelength router is required to route each wavelength to each of the ONUs connected to the network and finally, each ONU needs to transmit its upstream channel on a specific and unique wavelength, cutting the number of potential terminals to halve the number of wavelengths available. For that last purpose, if we want all ONUs to be identical, expensive tuneable laser sources are needed. If we want to use fixed lasers, each ONUs will need a different laser source, increasing enormously the complexity of the stock control. However, there are some concepts alleviating these problems, e.g., by spectral slicing each ONU may be equipped with the same type of broad spectrum source, see section 4.3. Alternatively, one may also use remote modulation at the ONU of a wavelength channel generated upstream in the shared part of the network, thus avoiding an active source at the ONU, see section 4.2. Another alternative is to use exchangeable transceiver modules and wavelength filters, e.g. OADM (Optical Add/Drop Multiplexer) modules.

2.2.4.1 Hybrid WDM/TDM PONs

To overcome the problems of WDM PONs, some solutions have been developed in the field of hybrid WDM/TDM in the last years. The idea is to mix both concepts to combine the better of the two options. The most accepted approach is to embed TDM PONs in a WDM PON, leading to a dense network capable of offering connectivity to a large number of users. This solution does not solve the fact that the ONUs should be different if we do not use tuneable lasers for them.

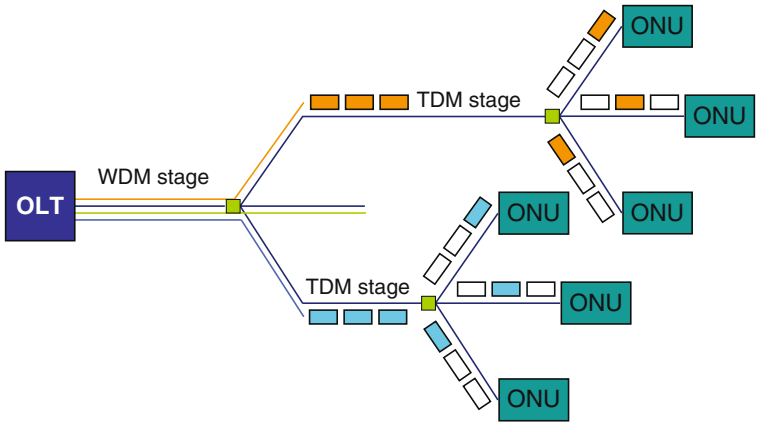

Fig. 2.8 Example of hybrid WDM/TDM topology

Another interesting approach that uses a hybrid WDM/TDM access method consists of sharing a laser stack among the ONUs connected to the network (Fig. 2.8). In that case, each tuneable laser switches to different wavelengths sending data on TDM basis to the different ONUs. This alternative also reduces costs because there is no need to allocate one laser for each ONU at the OLT. Also, from the network performance and utilization point of view, this idea is logical as ONUs are not transmitting all the time.

2.2.5 Reconfigurable WDM PONs

To cope with variation in service demand by the users and the sometimes quickly changing operator conditions, it is more efficient to flexibly allocate the augmented network capacity created by the multiple wavelength channels across the access network. Dynamic wavelength routing techniques can be used for this, thus making more efficient use of the network's resources and generating more revenues.

Figure 2.9 illustrates the principle: from the OLT in the head-end station of the network, multiple wavelength channels are fed to the ONUs via a tree-and-branch PON. By wavelength-selective routing in the PON or wavelength selection at the ONU, wavelength channels can be assigned to a number of specific ONUs. Thus capacity can be shared between these ONUs. The ONUs subsequently transfer these capacity shares to their first-mile electrical network connecting the end users. The mapping of the network capacity resources to the first-mile networks can thus be changed by altering the wavelength channel assignment. Basically two approaches can be followed for this, as illustrated in Fig. 2.10: wavelength routing in the field or wavelength selection at the ONUs.

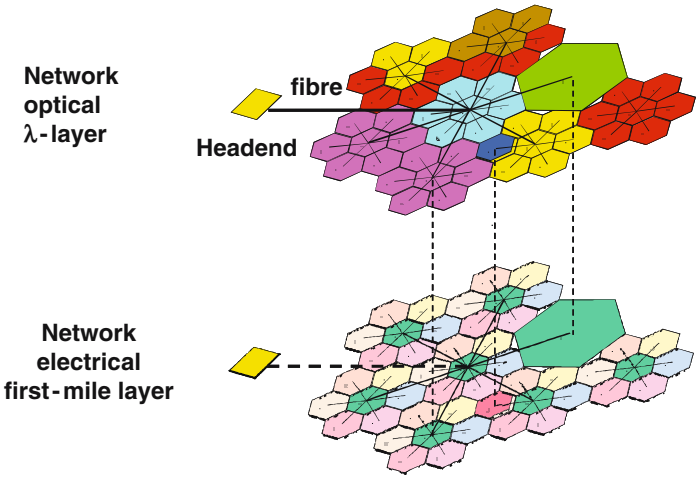

Fig. 2.9 Dynamic wavelength routing in hybrid access networks

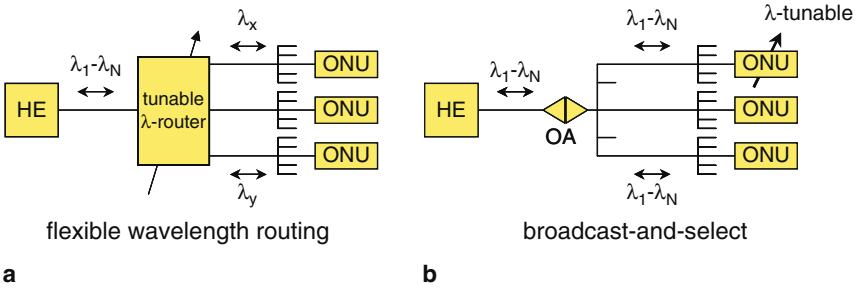

Fig. 2.10 Dynamic allocation of wavelength channels to the Optical Network Units (a) flexible wavelength routing (b) broadcast-and-select

With wavelength routing, as shown in Fig. 2.10a, a tuneable wavelength router directs the wavelength channels to specific output ports, and this routing can be dynamically adjusted by external control signals from the head-end. In order to support the delivery of broadcast services to all ONUs in addition, extra provisions have to be made to enable broadcast wavelength channel(s). Either the wavelength router must provide all switching or the broadcast channels need to bypass the router via an optical power splitter as discussed next with the wavelength selection scheme. As routed wavelength channels are distributed to only those ONUs whose customers require the associated services, no optical power is wasted.

With wavelength selection, as shown in Fig. 2.10b, all wavelength channels are broadcasted to every ONU and subsequently the ONU is tuned to the wanted

wavelength channel. Clearly the power of the other wavelength channels is wasted by the ONU and the losses at the broadcasting power splitter are significant. An optical amplifier is usually needed to compensate for these losses and has to operate bidirectionally to handle downstream as well as upstream traffic. On the other hand, no specific provisions in the network are needed to support broadcast services.

2.2.6 *Wavelength Broadcast-and-Select Access Network*

Figure 2.11 presents a multi-wavelength overlay of a number of ATM (Asynchronous Transfer Mode) PON networks on a Hybrid Fibre Coaxial (HFC) network, following

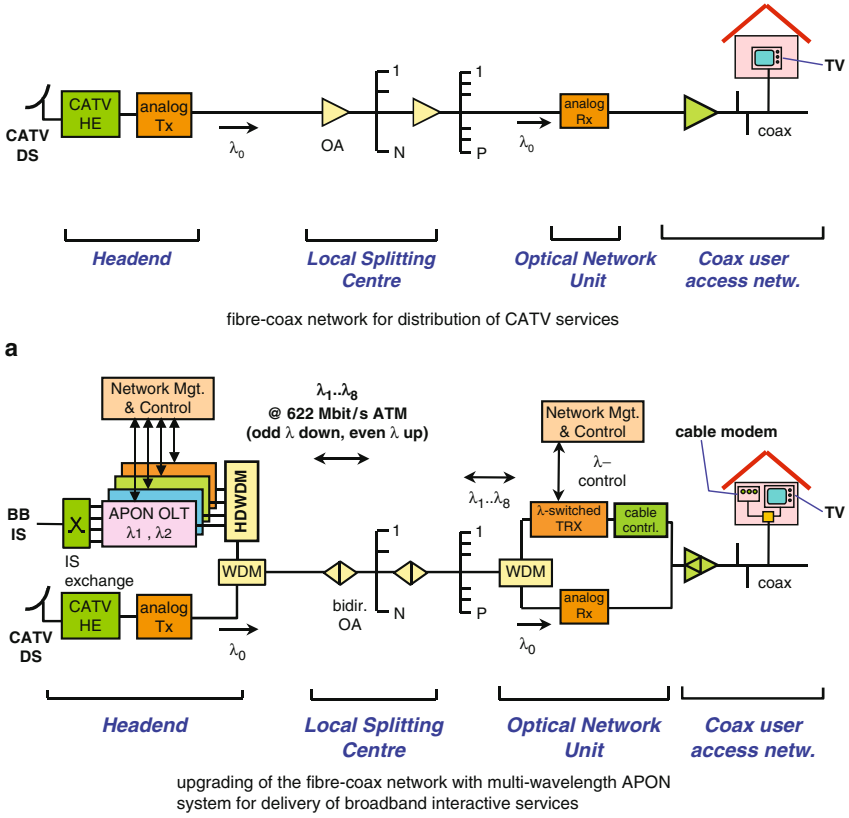

Fig. 2.11 Flexible capacity allocation in a multi-wavelength fibre-coax network by wavelength selection at the optical network units (a) fibre-coax network for distribution of CATV services (b) upgrading of the fibre-coax network with multi-wavelength APON system for delivery of broadband interactive services

the *wavelength channel selection* approach [Koonen97]. Figure 2.11a shows a fibre-coax network for distribution of Cable Television (CATV) services, operating at a wavelength λ_0 in the 1,550–1,560 nm window where erbium-doped fibre amplifiers (EDFAs) offer their best output power performance. Thus, using several EDFAs in cascade, an extensive optical network splitting factor can be realised and a large number of customers can be served. For example, with two optical amplifier stages, typical splitting factors of $N = 4$ and $P = 16$ (as defined in Fig. 2.11) and a mini-fibre node serving 40 users via its coaxial network, a total of 2,560 users is served from a single head-end fibre. For interactive services, the upstream frequency band in a standard HFC network (with a width of about 40–60 MHz) has to be shared among these users, thus allowing only limited bit rates per user for narrowband services such as voice telephony.

An upgrade of the system in order to provide broadband interactive services can be realised by overlaying the HFC network with a number of wavelength-multiplexed APON systems, as have been developed in the ACTS TOBASCO project and are shown in Fig. 2.10b.

Four APON OLTs at the head-end site are providing each one bidirectional 622 Mbps ATM signal on a specific downstream and upstream wavelength. These eight wavelengths are positioned in the 1,535–1,541 nm window where the up- and downstream wavelength channels are interleaved with 100 GHz spacing.

The APON wavelengths are combined by a High-Density Wavelength Division Multiplexer (HDWDM), and subsequently multiplexed with the CATV signal by means of a simple coarse wavelength multiplexer (thanks to the wide spacing between the band of APON wavelengths and the CATV wavelength band). The system upgrade implies also replacement of the unidirectional optical erbium-doped fibre amplifiers by bidirectional ones which feature low noise and high power operation for the downstream CATV signal and for the bidirectional ATM signals a wavelength-flattened gain curve plus a non-saturated behaviour (to suppress crosstalk in burst-mode). At the ONU site, the CATV signal is first separated from the APON signals by means of a coarse wavelength demultiplexer and is subsequently converted to an electrical CATV signal by a highly linear receiver and distributed to the users via the coaxial network.

The APON (Asynchronous Transfer Mode Passive Optical Network) signals are fed to a wavelength-switched transceiver, of which the receiver can be switched to any of the four downstream wavelength channels, and the transmitter to any of the four upstream ones. The wavelength-switched transceiver may be implemented by an array of wavelength-specific transmitters and receivers which can be individually switched on and off. This configuration allows to set up a new wavelength channel before breaking down the old one ("make-before-break"). Alternatively, it may use wavelength-tuneable transmitters and receivers, which can address any wavelength in a certain range in principle. This eases further upgrading of the system by introducing more wavelength channels, but also implies a "break-before-make" channel switching. The network management and control system commands to which downstream and to which upstream wavelength channel each ONU transceiver is switched. By issuing these commands from the head-end station, the net-

work operator actually controls the virtual topology of the network and thus is able to allocate the network's capacity resources in response to the traffic demands at various ONU sites.

The network management command signals are transported via an out-of-band wavelength channel in the 1.3 µm wavelength window. The APON signal channel selected by the ONU is converted into a bidirectional electrical broadband data signal by the transceiver; this is done by a cable modem controller tuned to the appropriate frequency band for multiplexing with the electrical CATV signal. The upstream data signal is usually put below the lowest frequency CATV signal (so below 40–50 MHz) and the downstream signal in empty frequency bands positioned between the CATV broadcast channels. The signals are carried by the coaxial network (in which only the electrical amplifiers need to be adapted to handle the broadband data signals) to the customer homes, where the CATV signal is separated from the bidirectional data signals. The latter signals are processed by a cable modem, which interacts with the cable modem controller at the ONU site.

By remotely changing the wavelength selection at the ONUs, the network operator can adjust the system's capacity allocation in order to meet the local traffic demands at the ONU sites.

As illustrated in Fig. 2.12, the ONUs are allocated to the four upstream (and downstream) wavelength channels which each have a maximum capacity of 622 Mbps for ATM data. As soon as the traffic to be sent upstream by an ONU grows and does not fit anymore within its wavelength channel, the network management system can command the ONU to be allocated to another wavelength channel, in which still sufficient free capacity is available. Obviously, this dynamic wavelength re-allocation process reduces the system's blocking probability, i.e. it allows the system to handle more traffic without blocking and thus can increase the revenues of the operator.

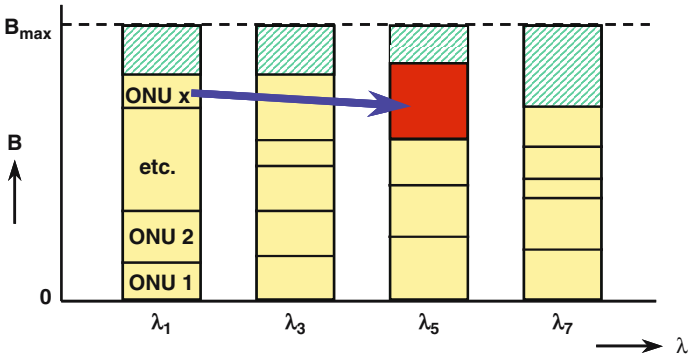

Fig. 2.12 Re-allocating Optical Network Units to wavelength channels

2.2.6.1 Hybrid WDM/TDM PONs

While under low traffic conditions dynamic bandwidth allocation can be obtained at the access protocol level on a time-sharing basis, this may not be sufficient under highly loaded conditions since the needed aggregated bandwidth may exceed wavelength capacity. If WDM is used and ONUs are provided with tuneable transceivers, nodes can be re-tuned (re-configured) to less loaded wavelengths to equalize traffic among all available wavelengths, thereby increasing the network capacity.

Although tuneability is required at the ONUs to dynamically assign wavelengths to transceivers, this tuneability does not need to be fast since it must track slow traffic changes (i.e., changes on an hourly or daily time scale). Nowadays, slow tuneable filters and lasers are becoming cheap devices so that these solutions can be considered affordable in a PON scenario in the near future.

Reconfigurable PONs build different logical topologies over the fibre network which can properly match traffic conditions and follow slow traffic changes. A decision problem concerning how to build these logical PONs arises. Thus, efficient reconfiguration mechanisms that solve this problem need to be studied.

It is essential that WDM/TDM PON solutions do coexist with current TDM PON solutions so that the field-deployed PON infrastructure can be left untouched if economical migration/upgrading is intended. In that case, changes/upgrades should only be done in the OLTs at the Central Office (CO) or in the ONUs at the subscriber side so that the modifications in the current infrastructure are minimal.

A preliminary analysis of a possible upgrade for current PON solutions with capabilities of reconfiguration was carried out. A simple and cost effective approach could be to introduce CWDM only in the downstream and leave the upstream untouched (upstream based on TDM only) as shown in Fig. 2.13. If so, the OLT must be equipped with an array of lasers to transmit on the different wavelengths, and ONUs should have slow tuneable (hence cheap) filters to receive on a selectable single wavelength. As a consequence, one logical PON is built for each laser of the

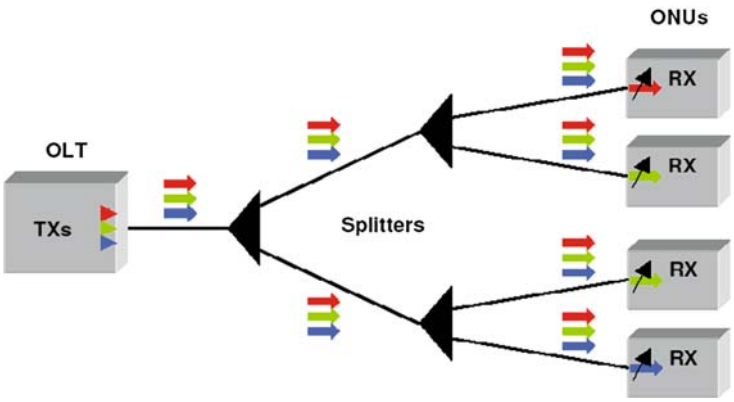

Fig. 2.13 WDM/TDM in the downstream path

OLT and each ONU can belong to anyone of these by just deciding on which wavelength the reception takes place.

A decision problem arises that concerns how to assign ONUs to wavelengths, known as the Dynamic Wavelength Assignment (DWA) problem. Good solutions should equalize the offered traffic among all wavelengths and avoid overload-conditions. Since the OLT schedules all downstream traffic (i.e., it knows the downstream traffic matrix), it can find the logical PONs needed to match the current traffic best. Although this problem can be solved optimally, it has been demonstrated to be NP-hard. However, a fast heuristic known as Longest Processing Time (LPT) can be used to solve it in polynomial time.

Since tuneability is slow, the ONUs go offline during the process of retuning for what we call a *blackout period,* during which they cannot receive packets. Therefore, when looking for traffic-matched logical topologies, it is also important to consider the reconfiguration cost (i.e., the number of reconfigured ONUs) associated for moving from one logical PON to another. Reconfiguration algorithms should not only look at traffic equalization but also at possible traffic disruption.

Both the optimal solution and heuristic approaches to a similar problem have been proposed and studied in [Neri05].

In order to improve bandwidth allocation also for upstream traffic (for example, for peer-to-peer traffic) (C)WDM can be introduced in the upstream path by equipping ONUs with slow tuneable transmitters and the OLT with an array of fixed receivers, as sketched in Fig. 2.14. Today the cost of CWDM tuneable lasers is only 15–20% higher then the cost of a fixed laser (with the same power and spectral features). Again a decision problem arises for deciding to which wavelength ONU transmitters should be tuned. However, while for downstream traffic the OLT knows the traffic matrix, for upstream traffic this information is distributed among nodes. On the contrary, blackout times are not as critical as in the downstream case since transmitters could be retuned in a distributed fashion without any packet loss (i.e., packets remain on buffers until the retuning is over).

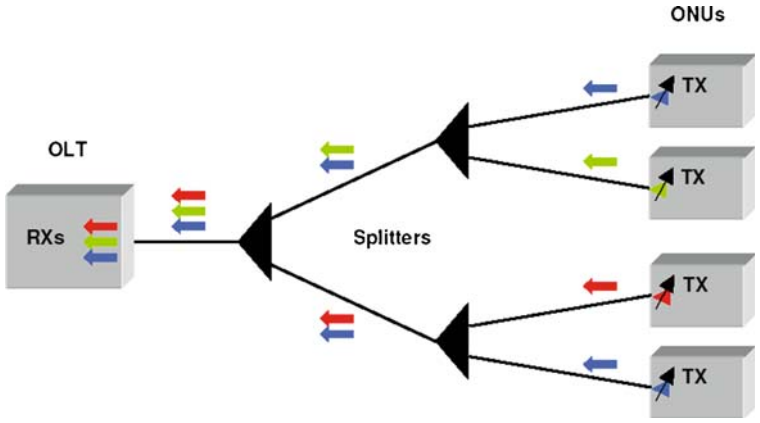

Fig. 2.14 WDM/TDM in the upstream path

2.2.7 *Wavelength Routing Access Network*

Figure 2.15 presents the *dynamic wavelength channel routing* approach in a fibre-wireless network to allocate flexibly the capacity of a number of ATM PON systems among ONUs in a single fibre split network infrastructure [Koonen00], [Koonen01]. The ONUs are each feeding a radio access point (RAP) of e.g. a wireless LAN (Local Area Network), which wirelessly connects to a variable number of users with mobile terminals. These users move across the geographical area served by the network (e.g. a business park) and they may want to set up a broadband wireless connection to their laptop at any time anywhere in this area. When many users are within a wireless cell served by a certain RAP, this cell may have to handle much more traffic than the other cells; it has become a "hot spot" which has to be equipped with additional capacity.

The corresponding RAP may switch on more microwave carriers to provide this additional capacity over the air and also has to claim more capacity from the ONU. This local extra capacity can be provided by re-allocation of the wavelength channels over the ONUs which is done by a flexible wavelength router positioned in the field. Similar to the architecture of the wavelength-reconfigurable fibre-coax network in Fig. 2.11b, the architecture in Fig. 2.15 developed in the ACTS PRISMA project has four 622 Mbps bidirectional APON OLTs with a specific downstream wavelength and an upstream one each. The four downstream wavelengths are located in the 1,538–1,541 nm range, with 100 GHz spacing, and the four upstream ones in the 1,547–1,550 nm range with the same spacing. The flexible wavelength router directs the downstream wavelength channels each to one or more of its output ports and thus via a split network to a subset of ONUs. The RAPs could operate with up to five microwave carriers in the 5 GHz region, each carrying up to 20 Mbps ATM WLAN data in the OFDM (Orthogonal Frequency Division Multiplexing) format.

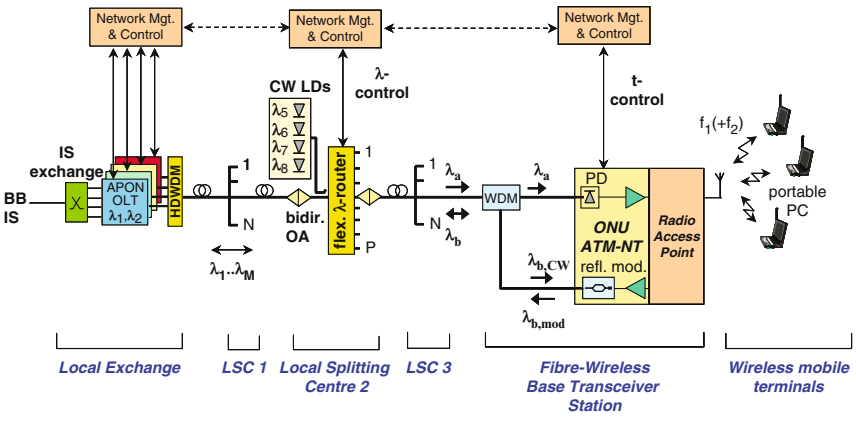

Fig. 2.15 Flexible capacity assignment in a multi-wavelength fibre-wireless network by wavelength routing in the field

At the flexible router (or at the local exchange) a number of continuous-wave emitting laser diodes, which provide unmodulated light power at the upstream wavelengths, are located. The flexible router can select one of these upstream wavelengths and direct it to the ONUs that can modulate the signal with the upstream data and return it by means of a reflective modulator via the router to the local exchange. Thus no wavelength-specific source is needed at the ONU ("colourless ONU"), the downstream light sources are shared by a number of ONUs and all ONUs are identical, which reduces the system costs and the inventory issues. The flexible wavelength router can be implemented with a wavelength de-multiplexer separating the wavelength channels, followed by power splitters, optical switches and power couplers in order to guide the channels to the selected output port(s). Depending on the granularity of the wavelength allocation process, the flexible router may be positioned at various splitting levels in the network.

Using a similar strategy to assign wavelength channels to the ONUs as depicted in Fig. 2.12, a statistical performance analysis has been performed of the blocking probability of the system. It was assumed that the total network served 343 cells, of which 49 were "hot spots", i.e. generated a traffic load two times as large as a regular cell. It was also assumed that the system deployed seven wavelength channels, and that the calls arrived according to a Poisson process where the call duration and length were uniformly distributed. Figure 2.16 shows how the system blocking probability depends on the offered load (normalised on the total available capacity, which is 7 × 622 Mbps), using various system architecture options. When wavelength re-allocation would not be possible (i.e. static WDM) and all the 49 hot spots were positioned at cells served by ONUs assigned

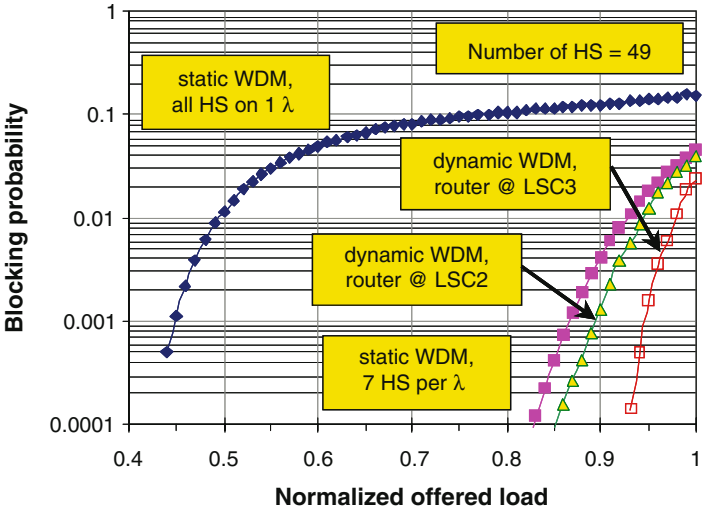

Fig. 2.16 Improving the system performance by dynamic wavelength allocation

to the same wavelength channel, the blocking probability is obviously the worst case. On the other hand, in the static WDM case when the 49 hot spots were evenly spread over the seven wavelength channels, the blocking probability is much lower (i.e., best case). Unfortunately, a network operator cannot know beforehand where the hot spots will be positioned, so in this static WDM situation the system blocking probability will be anywhere between the best case and the worst case, and no guarantee for a certain blocking performance can be given. However, when dynamic re-allocation of the wavelength channels is possible, the system can adapt to the actual hot spot distribution. Figure 2.16 shows that when the flexible wavelength router is positioned at the second splitting point (LSC2) in the network, the blocking performance is better than the best-case static WDM performance; but more importantly, it is also stable against variations in the hot spot distribution and thus it would allow an operator to guarantee a certain system blocking performance while still optimising the efficiency of his system's capacity resources. The blocking performance may be even better and stable when positioning the flexible router at the third splitting point; however, this implies that the costs of the router are shared by less ONUs which results in a higher cost per user. Locating the router at the second splitting point is a good compromise between adequate improvement of the system blocking performance and system costs per ONU.

2.3 Geographical, Optical and Virtual Topologies: Star, Tree, Bus, Ring and Combined

Figure 2.17 shows the basic topologies that are currently used in access networks.

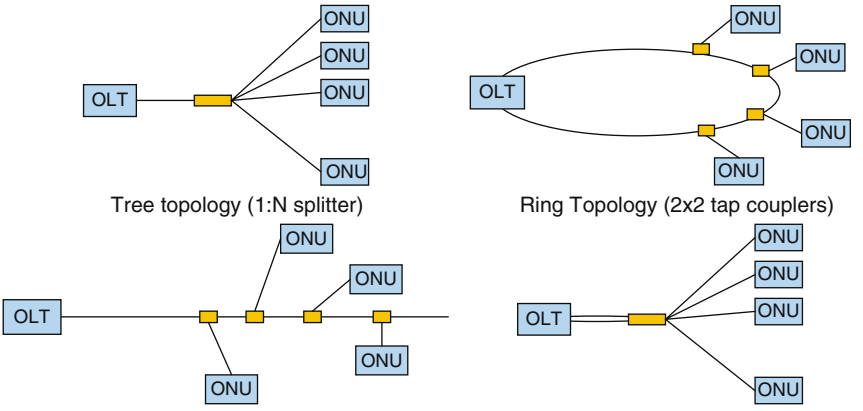

Fig. 2.17 PON topologies Tree topology (1:N splitter) Ring Topology (2 × 2 tap couplers) Bus topology (1:2 tap couplers) Tree with redundant trunk (2:N splitter)

2.3.1 Tree Topology

It is the most commonly used in access networks and uses a single fibre from the OLT to an intermediate splitting point. From this splitting point, there is a fibre for each ONU connected to the network. In principle the tree topology consists of cascaded splitting points and topologies with a single splitting point are in general termed as star topology. However, due to the special relation between OLT and ONU there is directivity and therefore this topology, if applied to access networks, is commonly termed as tree topology.

The main advantage of this topology is that the splitting is concentrated on a single point; thus it is simple to detect a network problem. Another advantage is that all ONUs have the same power budget which means that they all will receive roughly the same optical signal quality.

This architecture allows that the OLT equipment, which is the enabling equipment for processing capacity and transport capacity, to be shared among all ONUs and makes only use of fairly mature low cost optical components. In addition, the point-to-multipoint connectivity of a PON also reduces fibre congestion potential at the OLT site compared to a pure point-to-point approach. The number of ONUs that can be supported is limited either by the splitting loss in the star coupler or the required bandwidth per user. Note that all users need to fit to the capacity of the OLT splitter link and thus the potential of sharing capacites limits the number of active users.

The star topology (single splitting point topology) is attractive due to the fact that the transfer from a narrowband last mile technology (up to 2 Mbps per customer) to a fibre based broad-band access network (at least 1 Gbps shared capacity per ONU) is easy and effective. If the number of subscribers increases, the star network can be easily broken up into several subnets adding another splitter and OLT to the splitter link, yielding a versatile and flexible architecture for network expansion.

Commonly star topologies involve a passive optical broadcast star splitter device, which simply splits all the optical power independent of wavelength and port. This broadcast star architectures may have tuneable transmitters and fixed receivers, tuneable receivers and fixed transmitters, or tuneable transmitters and receivers if WDM is used to separate feeds to/from different ONUs, which efficiently increases the network capacity but also the cost.

The basic architectures however use TDM only, i.e. use an a priory timeslots assignation between ONUs and OLT, as differences in fibre lengths between splitting point and ONUs need to be considered for upstream transmission in order to avoid collisions on the OLT to splitter link. ONUs typically use the assigned ONU-OLT capacity dynamically to transmit feeds from the different customers currently connected.

Stars present a weakness in terms of reliability. Failure of the central device can bring down the whole network, but a total failure of a passive broadcast element is unlikely. However, many partial failure scenarios exist, including amplifier failures, port connection failures at the access nodes, transmitter or receiver failures at access nodes (e.g., because of laser failure or tuning skew) and cabling failures in

the fibre network. Such failures generally lead to failure of one or more arms of the star. In case of access networks a failure of the OLT to splitter link is fatal as that efficiently affects all communication.

Another drawback is that the available bandwidth is shared by all customers on the trunk connection from OLT to the optical splitter. The average capacity share per customer is thus the number of wavelengths multiplied by the bit rate per wavelength divided through the total number of customers. For example eight wavelengths at 2.5 Gbps shared by 200 customers result in an average capacity per customer of 100 Mbps. If this value shall be guaranteed, the customer traffic must be limited to this rate which in turn deteriorates the network utilisation as typically not all customers access that capacity constantly.

2.3.2 Bus Topology

The bus topology uses also a single fibre from the OLT, thus the same worst case failure and capacity/utilisation issues arise as for the tree topology. Each final subscriber is connected to it by means of a tap coupler that extracts a small part of the power that is being transmitted from the OLT. The two advantages of this topology are that it is the one that uses minimal amount of optical fibre (if ONUs are directly connected to the tap coupler) and allows flexible deployments as a new ONUs can be connected to the network very easily by adding one more tap. The main problems are: on the one hand, that the signal is degraded when passing through each tap coupler, and therefore the ONUs located far from the OLT are receiving weak and degraded signals; on the other hand, that the required total fibre length is high for covering a two-dimensional area.

2.3.3 Ring Topology

The ring topology is mainly used in metropolitan networks because it offers resilience capability with a minimal number links. As there are two possible ways to reach the OLT, it is still possible to establish and maintain a data link in case of a fibre cut. However, it requires two fibres to be used at the OLT and more complicated equipment at each ONU with switching capabilities to be able to send and receive the signals being transmitted from the two directions of the fibre ring. It also shows the same problem as the bus topology in terms of power budget. When the optical signal passes through each ONU, the signal is degraded and attenuated. This factor is the most restrictive one in terms of transmission capabilities and restricts the number of ONUs that can be connected to the ring. Capacity is also shared among all ONUs if resilience is used, thus the second fibre from the OLT does not increase the network capacity, i.e. the total number of customers is limited to the same number as for the tree and bus topology.

2.3.4 *Tree with Ring or Redundant Trunk*

This topology is identical to the standard tree topology but with the difference that two fibres are connected to the OLT for resilience purposes. In case one fibre is cut, the other can be used to transmit. However, when deploying the structure, these two fibres need to be installed on separated trunks to avoid both being cut at the same time. The optical star coupler however needs either to provide an active switch over facilities to select a trunk connection to/from the OLT or needs to distribute all data flows twice to all ONUs if these provide the switch over units. In latter case the maximum capacity per ONU trunk is halved. However, assuming a realistic splitting ration by far exceeding 1:2 at the star splitter, this restriction in general does not reduce the maximum number of customers supported at a guaranteed bit rate.

Combination of these basic topologies can offer granularity and a higher density as well as better applicability to cover two dimensional areas. The most promising approach is to mix a primary ring and secondary trees to offer resilience in the distribution feeder and optimization of fibre length deployment in the access segment (Fig. 2.18).

Another interesting approach is the double ring, which offers resilience on both, the primary and secondary segments of the access network (Fig. 2.19). However, this implies a more complex access protocol and more fibre deployment.

Relevant demonstrated projects that follow this advanced architecture are:

- SUCCESS (Stanford University aCCESS) [An04]
- HHI-CWDM [Langer06]
- SARDANA (Scalable Advanced Ring-based passive Dense Access Network Architecture) [Lazaro06]

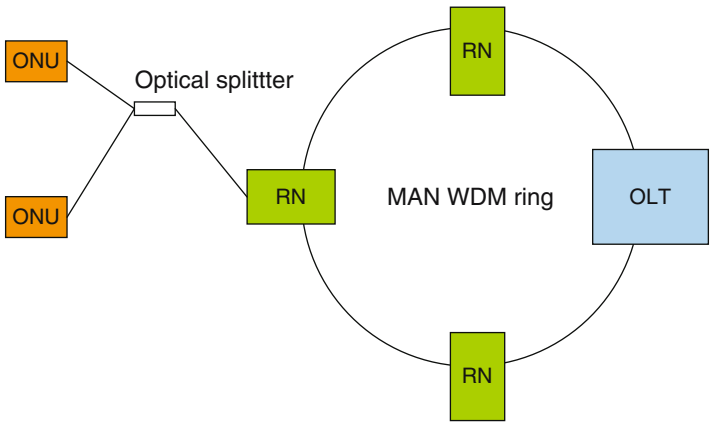

Fig. 2.18 Extended ring plus tree access topology

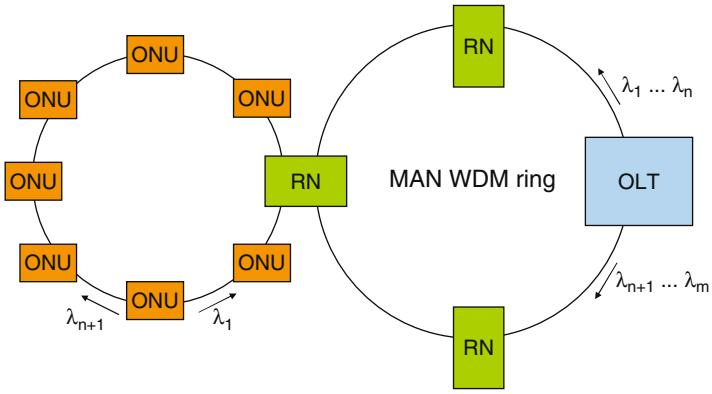

Fig. 2.19 Extended double ring access topology

2.3.5 *Arrayed Waveguide Grating Based Single Hop WDM/TDM PON*

Because of its non-blocking property an AWG hub in a passive-star WDM network leads to a potential connectivity of $N^2 \times N^2$, in case N represents the number of AWG ports, the number of wavelengths used and the TDM splitting to customers at ONUs. The considered network architecture is shown in Fig. 2.20 [Bengi02a].

Since no channel collisions occur at the AWG hub, the same wavelengths can be simultaneously used for multiple connections between different input/output pairs. Therefore AWG-based single hop networks offer superior bandwidth utilisation compared to passive star coupler architectures.

Note that for this architecture there is no OLT, there are only ONUs. Therefore this architecture provides peer connectivity as it is typically required for a Metropolitan Area Network (MAN). For application in access with single OLT and multiple ONUs, half of the ONUs shown need to be concentrated in the OLT in order to provide equal OLT to ONU capacity. Several proposals of such application exist, e.g. compare proposals given in section 2.2, some of them also make use of the special properties of AWGs.

Normally, N simultaneous transmissions can be simultaneously supported by one AWG if the number of ports equals the number of wavelengths, yielding a connectivity of N. In order to achieve a connectivity of up to N^2, $n \leq N$ customers can be attached to every AWG port, i.e. to every ONU, using TDM. Thus, such a network supports $M = n \times N$ customer terminals divided into N groups. Each wavelength channel can be divided into fixed-duration time slots and data packets fit into the so created TDM channels. Accordingly each node in a group may transmit and receive on any TDM channel available. However, channel as well as destination collisions need to be avoided, but only among the attached nodes of each group, as collisions with channels from other groups are not possible due to the wavelength

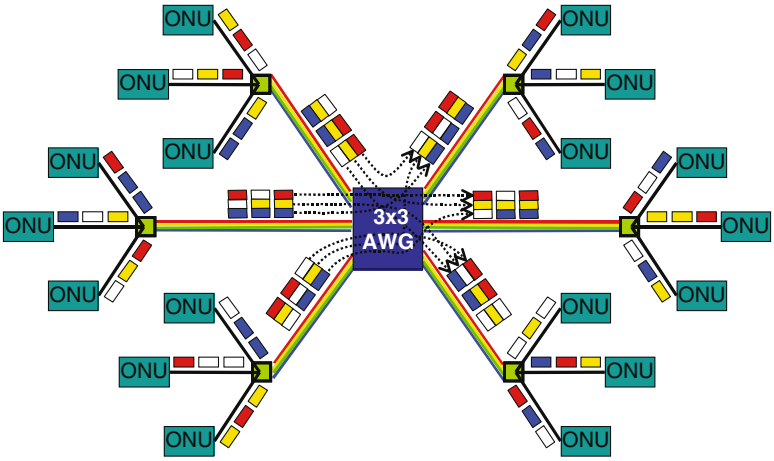

Fig. 2.20 Arrayed Waveguide Grating based single hop PON architecture

separation provided by the AWG. To assure that no collisions occur among channels of the sender and receiver groups, a specific scheduling algorithm is required – see section 6.2 for a detailed study.

Current TDM based PON networks are emerging as viable and cost effective access solutions for service providers facing extremely growing bandwidth demands per connection. Increasing the available bandwidth in the access will cause a dramatic increase of the connection bandwidths required for MANs to interconnect different service providers.

Especially to accommodate high quality peer services like video-conferencing and Storage Area Networks (SAN) installations across distant sites will make it necessary to efficiently use quickly adjustable bandwidth assignment strategies in order to economically utilise resources. Other services like video-on-demand are starting to emerge and create high volumes of asymmetric traffic with high QoS demands. In accordance with the ATM concept [ATM-Forum95], several QoS classes need to be supported such as CBR (Constant Bit Rate), VBR (Variable Bit Rate), traffic classified as real-time services, and ABR (Available Bit Rate) as well as UBR (Unspecified Bit Rate) traffic related to bursty data services. In general, for guaranteeing QoS requirements, a strong and resilient control on packet delays and node throughputs is essential and thus intelligent ONUs with dynamic capacity management are more and more required.

The prosperous application of WDM technology in backbone networks to achieve huge bandwidth channels (e.g. OTN/G.709 providing 2.5/10/40 Gbps channels) recommends the development and implementation of optical WDM technologies also for local and metropolitan area networks in order to enable access to these transport capacities, i.e. to eliminate the bottleneck between LAN and WAN.

2.4 Compatibility with Radio Applications UWB, UMTS, WiFi

In response to the increasing bandwidth offered by various technological solutions in access network (copper, fibre, radio), client demands are evolving to higher bit rates and also to the convergence of telecommunications networks, very separated up to now.

The increase of bandwidth in the access network is promoting the deployment of fibre. Although optical fibre solutions are still expensive and take time, it is important to foresee cost efficient optical solutions. The trend is to deploy hidden fibre closer and closer to the client in order to offer higher bit rate through xDSL and radio solutions (Wireless Fidelity WiFi, Worldwide Interoperability for Microwave Access WiMax). Fibre-to-the-Home (FTTH) is a long term solution. Techno-economical studies show that 30% of the fibre deployment costs in access are localized in the last hundreds of metres of the distribution network. This problem can be solved thanks to the progress on copper and radio systems as copper that is able to offer high bit rate but only over shorter distances (Very high rate Digital Subscriber Line, VDSL up to 100 Mbps over 150 m). It is being proposed using Fibre-to-the-Building (FTTB) PON solutions and new radio systems such as WiMax, which can perform 70–80 Mbps over the last mile, and Fibre-to-the-Curb (FTTC) PON solutions. The idea is therefore to reach a hybrid access network with an optical backhaul to be able to feed different network units, e.g. client equipment, a Digital Subscriber Loop Access Multiplexer (DSLAM) or a radio base station.

Radio technology is certainly the favourite technology of most of the providers. It eliminates cabling costs on the last hundreds of metres, i.e. the 30% of the deployment cost, but it has two main drawbacks: limitation of capacity and the problem of full coverage. Radio flexibility can allow the acceleration of broadband deployment in rural areas and it can offer a solution to an increasing demand of mobility. However, as the bit rate is increasing, the cell size decreases and the number of cells increases which leads to increased number of links to the fixed optical network. In parallel, radio technology is progressing and offers higher aggregated bit rate, and some new radio technologies are in development for a high rate Wireless Personal Area Network (WPAN) with shared data rates from 55 to 480 Mbps.

Considering these evolutions and the aggregated bit rates for wireless communication, optical fibre has become the most convenient media for feeding the different radio base stations (in optical networks 2.5 Gbps is the most commonly used bit rate; capacity of a single DWDM fibre is in the order of Tbps, e.g. $60\lambda \times 10/40$ Gbps), In this context, the next generation access system may take the different solutions to integrate optical fibre and radio into account.

Today, we can divide the wireless services into two main applications: wireless mobile (Global System for Mobile communications GSM, Universal Mobile Telecommunications System UMTS) and location based wireless (WiFi, WiMax). However, it seems that the trends in development of wireless applications lead to a merge between local solutions and mobile ones in order to offer high bit rate services in parallel with a high mobility. In this context, it is important that radio over fibre technologies support different wireless technologies which are probably going

to coexist in the service provisioning network. Thus the genericity of the optical distribution network is a key issue in order to justify its interest.

The development of PONs allowing the realisation of a multi-service multi-band radio over fibre network could lead to an efficient cost reduction for the Operating Expenditure OPEX (reconfigurability, unified maintenance) and for the Capital Expenditures CAPEX (share one infrastructure between services).

This evolution of the access networks is motivating the users to deploy new technology (best suited wireless) in order to share network access between equipment locally spread, e.g. across different rooms. The standard IEEE 802.11 (Institute of Electrical and Electronics Engineers) has quickly become a leading system for such an application, and future standard extensions likely will go beyond the current limits.

If we foresee wireless systems, the increasingly high carrier frequencies are quite suitable for radio over fibre technologies (Fig. 2.21). However, we have to differentiate the indoor application from the outdoor application.
Future wireless applications for outdoor context:

- Mobile: 3G, 3.5G, 4G (2 GHz band): Research teams are working on the development of key radio access technology for 4G mobile communications such as OFDM, MIMO (Multiple Input Multiple Output), and the increase in shared bit rate up to several hundreds of megabits per second seems to be possible in the same frequency band (around 2 GHz).

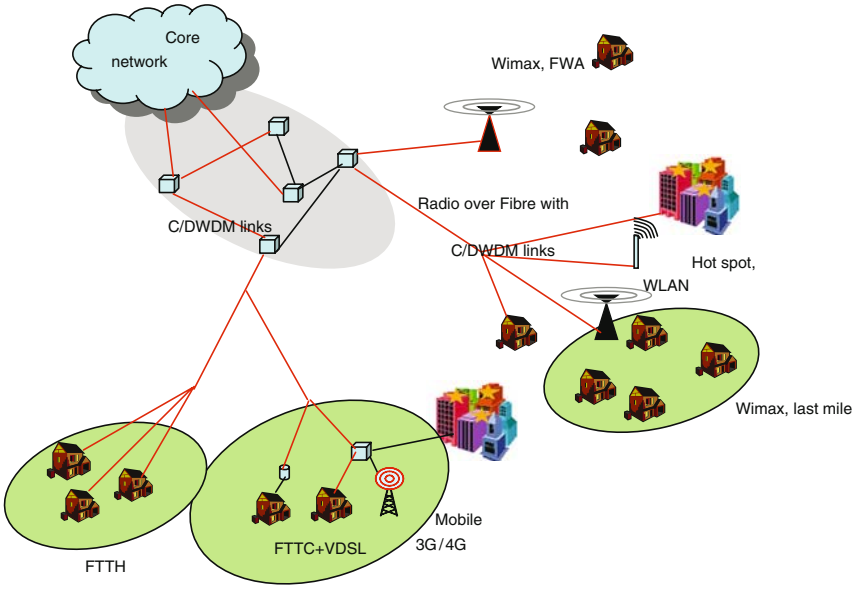

Fig. 2.21 Wireless and fibre common platform

- Location based: extension of Wireless LAN (WLAN) hot-spots using ad-hoc relaying functionality and WiMax broadband access service. Actual commercial solutions include WLAN: 2.4 GHz, 54 Mbps, point-to-point, and WiMax: 3.6 GHz, 80 Mbps, point-to-multipoint.

Future wireless technologies for indoor context:

- WiFi and IEEE802.11: The bandwidth demands are continuously increasing and the intrinsic contention problems demand to manage the QoS (Quality of Service) by offering hierarchical services, as higher penetration of IEEE 802.11 equipment induces a decrease in the spectral resources. This may not be a problem for the ngPON, as shown in earlier RoF demonstrations.
- Directed RF connections: Uncompromised multimedia services can more easily be realised with directed RF technologies as the base units (program source and sink) are in general either placed on some supporting cabinet or mounted to walls; i.e. they do not move during operation.

According to the target environment (public access point, private WLAN, multimedia home installations), different scenarios with different technical requirements for hybrid wireless-optic PON solutions can be defined by:

- Number of users
- Services and their QoS demands
- The maximum dedicated and aggregated bit rates
- Coexistence with other wireless access points (interference handling)
- Support for existent services such as Gigabit Ethernet (GBE), WLAN, and all kinds of wired modems, as well as for triple-play future services

In the access context, we have to keep the interoperability between the PON and its evolution by WDM with optical distribution of RF signals on dedicated wavelengths in mind.

The advantages of such architectures are:

- WDM and OLT management complexity in the central station
- Simple colourless duplexers in ONU and base station
- Fixed/wireless architecture compatibility and reconfiguration flexibility
- Multi-band multi-service duplexers

Also the radio signals may be distributed along the fibre infrastructure to the antenna sites in its microwave format, by so-called radio-over-fibre techniques; see section 2.5. This allows centralisation of the radio signal processing and thus may facilitate maintenance and upgrading of the wireless service provisioning.

2.5 Radio-Over-Fibre

Wireless communication services are steadily increasing their share of the telecommunication market. Next to their prime feature, the mobility, they are offering growing bandwidths to the end-users. This entails also an increase of the radio

carrier frequencies which leads to smaller radio cell coverage due to the increased propagation losses and line-of-sight needs. Wireless LANs in the 2.4 GHz range according to the IEEE 802.11b standard carry up to 11 Mbps, evolving up to 54 Mbps in the IEEE 802.11g standard. The IEEE 802.11a and the HIPERLAN/2 standard provide up to 54 Mbps in the 5.4 GHz range. Research is ongoing in systems that may deliver more than 100 Mbps in the radio frequency range well above 10 GHz (e.g., Local Multipoint Distribution Service LMDS at 28 GHz, HyperAccess at 17 and 42 GHz, Multipoint Video Distribution System MVDS at 40 GHz, MBS at 60 GHz, etc.).

Due to the shrinkage of radio cells at higher radio frequencies, even more antenna sites are needed to cover a certain area such as the rooms in an office building, in a hospital, the departure lounges of an airport, etc. Therefore more RAPs are needed to serve e.g. all the rooms in an office building and hence also a more extensive wired network to feed the RAPs. Instead of generating the microwave signals at each RAP individually, feeding the microwave signals from a central head-end site to the RAPs enables to simplify the RAPs considerably. The signal processing functions can thus be consolidated at the head-end site. This offers numerous advantages; e.g., maintenance and upgrading is facilitated, as for installing new functionalities only changes in the head-end site have to be made. Thanks to its broadband characteristics, optical fibre is an excellent medium to bring the microwave signals to the RAPs.

2.6 Next Generation G/E-PON Standards Development Process

Gigabit PON standards have been already standardized by the two reference standardization bodies (FSAN for GPON and IEEE for EPON) and deployments using them are taking place around the world. Now, in parallel with the technological advances at research and development stages on optical transmission and access networking, standardization bodies are considering the possible next generation upgrades of PONs. IEEE is taking a resolute position towards increasing the bit rate to 10Gbit/s, while FSAN has begun to evaluate different strategies [Hajduczenia06].

2.6.1 Development of 10G EPON

2.6.1.1 Introduction

The kick-off of the 10G EPON (Ethernet Passive Optical Networks) system standardization process under the auspices of IEEE [IEEE802cfi] back in 2006 brought around a new wave of interest in the evolution of the current single Gigabit PON systems towards high data rate systems capable of providing reliable, economic and future-proven platform for the delivery of subscriber oriented and personalized triple-play services. The Ethernet in the First Mile (EFM) Task Force (TF) was

disbanded in June 2004, having completed its task of developing and having ratified the IEEE 802.3ah specifications, now making part of the IEEE 802.3–2005 standard. The following 2 years saw unprecedented field deployment of EPON systems [Kramer06], [Kikushima06], [Mukherjee06], [Shraga05], [Abrams05], resulting in the currently installed port capacity, estimated at approximately 6 million deployed lines and 15 million ports installed in the CO (Central Office) of Service Providers (SPs) (port numbers valid for March 2007), in its different versions.

This way, Ethernet PON is likely to become a network of a choice for low cost, subscriber oriented digital service delivery, taking over the market previously dominated by DSL and cable modems. In this subsection, we will therefore examine in more detail the current development process of 10 Gbps EPON systems, standardized in the framework of the IEEE 802.3av TF, looking at the technical challenges, drivers and evolution scenarios of the emerging high data rate access systems.

Following their Ethernet heritage, EPON products exhibit a similar evolution curve, which led from first 10 Mbps CSMA/CD (Carrier Sense Multiple Access with Collision Detection) Ethernet systems through Point-to-Point (P2P) 100 Mbps LAN Ethernet towards current top-of-the-line 10 Gbps Ethernet lines in many flavours. It is observed that the mass deployment of legacy, IEEE 802.3ah compliant EPON systems resulted in a significant price decrease, with the cost slash downs of roughly 50% for complete EPON solutions and up to 70% for optical transceiver modules [Teknovus07]. The intensive research fuelled by the market competition and growing customer demand resulted in a number of new EPON products, namely quad-OLT Application-Specific Integrated Circuits (ASICs), System on Chip (SoC) allowing for the miniaturization of the ONUs, T1/E1 circuit emulation mechanisms for EPON networks with jitter and wander within ITU-T specs, etc., further improving the QoS for these once best-effort systems.

2.6.1.2 10G Ethernet PON Drivers

The effective data rate of 1 Gbps supported by the legacy IEEE 802.3ah compliant EPONs is already not considered sufficiently future-proven to assure revenue growth within the next few years, mainly due to increased customer demand for bandwidth intensive applications and explosive utilization of High Definition Television (HDTV) and online gaming, once available in the coverage area. Thus, development of higher capacity EPON systems was advocated in 2006 during one of the IEEE plenary meetings [IEEE802cfi], resulting in the initial establishment of the 10G EPON Study Group. This Study Group identified the market potential and evaluated the technical feasibility of the future 10G EPON systems, resulting in submission of the Project Authorization Request (PAR) and its subsequent approval at the subsequent IEEE Plenary meeting. Effectively, the 10G EPON Study Group was officially transformed into 10G EPON TF, identified as IEEE 802.3av, which is chartered with development and standardization of 10G EPON systems, provid-

ing increased channel capacity for both upstream and downstream channels, while maintaining the logical layer intact, taking advantage of the already existing MPCP (MultiPoint Control Protocol) specifications, which will remain backward compatible with legacy 1 Gbps EPONs.

The subsequent system architecture evaluation process indicated that the future 10G EPON equipment must provide a gradual evolution path from the currently deployed 1 Gbps equipment, thus both symmetric and asymmetric data rates must be supported for both downstream and upstream channels. Since such an evolution process inherently assumes coexistence with legacy IEEE 802.3–2005 EPONs on the same ODN (Outside Distribution Network) plant, the 10G EPON TF has therefore to resolve a number of technical issues, including the wavelength allocation issues for both data channels in a satisfactory manner, providing feasible technical solutions, especially in the upstream channel, as discussed below. As for this moment, no motions regarding the coexistence issues are officially approved by the TF. Nevertheless, a strong consensus exists in the group regarding the following issues:

- Coexistence is mandatory to assure a smooth transition path from 1 to 10 Gbps equipment and to avoid a significant one time investment into such a cost sensitive market (CAPEX).
- The wavelength allocation plan for 10 Gbps EPON systems must take into account the existence of 1 Gbps equipment on the same PON plant for both downstream and upstream channels.
- The mentioned wavelength allocation plan must also account for the existence of a downstream analogue video delivery service, which will most likely be maintained in future 10G EPON systems, mainly due to already existing equipment and significant CAPEX investment.
- Due to incompatible data rates (1 Gbps EPONs use 8B/10B encoding increasing the data rate to 1.25 GBd while 10 Gbps EPONs will most likely use 64B/66B encoding with PMD (Physical Media Dependent) level data rate of 10.3125 GBd), the downstream channels for the two data rates will be WDM multiplexed, with 1 Gbps using 1,490 ± 10 nm window and the 10 Gbps using the 1,574–1,600 nm window, further subdivided into 1,574–1,580 nm channel for PR30/PRX30 and 1,580–1,600 nm channel for PR10/PR20 PMDs, resulting from the particular requirements of the high power budget systems and limitations on the available wavelength allocation window due to the existence of OTDR (Optical Time Domain Reflectometry) filters in the ODN.
- The upstream channel coexistence will be resolved via TDM multiplexing, where different data rate bursts will be received by the OLT, identified and then processed accordingly (the so-called dual rate burst mode transmission). The selected solution presents a number of technical hurdles which will have to be overcome, such as burst data rate detection, adjustment of transamplifier gain, etc., and are currently under intensive study.

Since the transition process from legacy 1 Gbps equipment towards fully symmetric 10 Gbps network will be gradual in most cases and will require signifi-

cant modifications of the active equipment in the deployed EPON, it is prudent to be aware of a number of technical hurdles which lie ahead in this process. It was therefore our intent to study in more detail the evolution process, divided into three major stages, all of which are optional but are likely to occur in the existing networks.

2.6.1.3 Technical Challenges During Transition from 1 Towards 10 Gbps Ethernet PON Systems

The transition towards the fully symmetric 10 Gbps solutions should provide a smooth and gradual evolution path, where only parts of the active network equipment can be replaced at a time, allowing the network operators to distribute the necessary CAPEX investment in time. During the transition phase, both legacy 1 Gbps and emerging 10 Gbps equipment must coexist on the same PON plant, maintaining the operating parameters for both systems. This requires investigation of the wavelength allocation scheme, especially for the upstream channel, due to the current occupation of the complete 1,310 nm transmission window by the legacy 1 Gbps equipment, which demands either TDM sharing with varied data rates for the subsequent bursts or transmission outside of the 1,310 nm band, putting more strain on the laser sources and making the system less cost effective.

Dynamic Bandwidth Allocation Mechanisms

The DBA mechanism will not change in most cases when the transition between the 1 to 10 Gbps systems is under way. The IEEE 802.3av TF will not have any impact on the DBA mechanism specification and implementation, since the MPCP framework will be only extended in a backward compatible manner, not impacting the operation of legacy equipment.

What remains certain is the fact that the DBA implementation will still rely on the underlying MPCP layer, which in this case will become responsible for scheduling not one but two mutually cross dependent EPON systems. In the downstream channel, since the 1 Gbps and 10 Gbps data paths will be separated via WDM multiplexing, the DBA agent can schedule the transmission of the GATE MPCP Data Units independently. However, the upstream channel is more problematic, for a number of reasons.

- The employed line coding is different in the two systems, and thus two MAC (Medium Access Control) stacks will have to be implemented (at least the Reconciliation Layer and lower sections – PCS (Physical Coding Sublayer), PMA (Physical Medium Attachment) etc., due to different encoder/decoder functions as well as different Forward Error Correction (FEC) mechanisms, which were optional in 1G EPONs and will be mandatory in 10G systems), resulting in two MAC service interfaces presented to the MAC client layer. Current DBA

implementations do not provide means to connect to two such interfaces simultaneously and process the incoming data.

- The second technical hurdle is related with the underlying clock rate for 1 and 10 Gbps signals, which are not even multiples of each other, causing concerns about the internal MAC client layer jitter, should the DBA operation be based on a single clock rate only. Such an implementation would additionally suffer from time drift problems, since the Time Quantum (TQ) will have to be the same for both system, though representing a different number of bits – 16 ns in 1 Gbps is equal to 16 bit times, while 16 ns in 10 Gbps represents 160 bits, thus lowering the granting resolution. Even though the MPCP and the DBA implementations are data rate agnostic and use time references expressed in bit times, in practice the observed clock rate incompatibilities might impact the scheduling precision of 1 Gbps DBA, should it be operated with the 10 Gbps system clock rate.
- The detailed internal structure of the DBA agent is not and will not be standardized by the IEEE 802.3av TF, though future implementations will have to be selected whether two independent DBA agents are implemented (for 1 and 10 Gbps independently) separately and then linked via a third entity, or whether a single DBA agent is implemented and data rate detection is allowed in the process. One way or another, the DBA implementation will present a number of technical problems, which will have to be resolved should the coexistence between legacy and new equipment is to be assured.

Security Considerations

The basic security threats taunting the future 10 Gbps EPON systems will be inherently identical with those characteristic of all PON network structures. Since the transmission channel is passive and uses optical fibre instead of a standard copper line transmission medium, it is believed that there is no electromagnetic interference and thus no way to eavesdrop the data stream. This particular idea probably stems from comparison of optical and wireless networks with their broadcast transmissions and ease of eavesdropping in the latter. However, data mining and in particular passive monitoring is also possible in PON systems, and actually constitutes one of the first attacks to be attempted upon such networks. In a PON environment (the problem is shared by all PON systems, regardless of the utilised Layer 2 scheduling and framing mechanism), eavesdropping is always possible in the downstream direction simply by placing one receiver connected to the line in the users premises or by operating an ONU in a so-called promiscuous mode. Since each ONU in the network receives a copy of all downstream packets transmitted by the OLT, no extensive modifications are required in the ONU hardware to enable its malicious operation – it is only sufficient to disable the LLID (Logical Link Identifier) filtering rules and enjoy unrestricted access to all information transmitted in the downstream channel. What makes the situation worse is that the employed eavesdropping method is completely passive, remotely undetectable and does not trigger any visible side-effects in the network structure/behaviour.

The upstream channel is considered more secure, since the network architecture prevents other subscribers from eavesdropping transmission contents from other stations at the hardware level. Only the OLT receives ONU transmissions and is aware of the activity periods of individual ONUs. It was argued [Kramer03], that the presence of a Passive Star Coupler (PSC) in the transmission path might introduce sufficient signal reflections (with enough amplification) to reconstruct upstream transmissions originating from other ONUs in the network. However, it has not been proven practically, until now, that such a vulnerability might be exploited [Pohjola05].

There is however some improvement to be observed in terms of the security of the data stream transmitted in the PON environment during the evolution phase. The target data rate of the EPON system increases roughly ten times, requiring the potential attackers to use more expensive, technologically advanced means of intercepting transmission, storing its contents and processing later on, in the attempt to carry out the passive monitoring attack. Current computer technology does not allow for direct information processing at the 10 Gbps line rate, assuming that parallel processing techniques are not utilized.

The evolution of the EPON systems from 1 to 10 Gbps additionally introduce an interesting security aspect, since during the transition phases 1 and 2 (as described below), a person in the middle attack would require a complete implementation of the OLT hardware, accounting for the fact that the upstream bursts can arrive at any supported data rate. Reception of both downstream and upstream channels would therefore require four independent receiver modules (two for downstream and two for upstream), connected together with a complex electronic processing module capable of analyzing incoming data streams at the line rate. The resulting technical hurdles may therefore be too difficult to overcome in the near future, especially when taking into account the fact that most EPON equipment vendors provide hardware level AES-128bit + (Advanced Encryption Standard) quality data encryption. However, it is not possible to predict the development path of computer hardware and the resulting increase in the accessible computational power, which may prove one day capable of breaking the AES encryption at the channel rate.

1G and 10G Ethernet PON Coexistence on the Same PON Plant

The 1G and 10G EPON coexistence requirement will inherently result in the creation and deployment of very complex PON systems, where two partially independent transmission systems will share a single PON plant, thus resulting in the need to share both downstream and upstream channels in a way which eliminates crosstalk and signal quality degradation. As indicated before, the downstream 1G and 10G data streams will be WDM multiplexed, resulting in two independent, continuous Point-to-Multipoint (P2M) channels, separated by a sufficiently large bandwidth gap allowing for their uninterrupted operation under any temperature conditions accounted for in the IEEE standard. The 1G downstream link will therefore remain centred at 1,490 nm with the 20 nm window size, while the new 10G

downstream link will be allocated in the 1,574–1,580 nm band for PR30/PRX30 systems and 1,580–1,600 nm band for PR10/PR20 systems. The channel allocation above the current analogue video service delivery band is a better option (above 1,560 nm), mainly due to limited nonlinear impairments and lower 10G signal degradation. The commercial availability of laser and receiver units was already proven by the members of the TF, indicating that such a channel allocation can be supported using existing technology.

Figure 2.22 depicts the most complete 1G/10G EPON system with legacy 1G symmetric ONU as well as emerging IEEE 802.3av compatible 10G/1G and 10G/10G ONUs (symmetric and asymmetric modules), sharing the same PON plant. As indicated before, in the downstream channel a WDM multiplexing technique is used, thus limiting technical hurdles to proper ONU triplexer design (more precisely, proper filter design for 10G ONU triplexers). In the upstream channel, the WDM multiplexing is discouraged mainly by the chromatic dispersion observed for low grade laser sources outside of the 1,310 nm window, which is already allocated for 1G EPONs. Since the 1G specifications cannot be modified with the compliant equipment being mass deployed in field, only burst mode TDM multiplexing remains a viable option, which is illustrated in Fig. 2.22. Both 1G and 10G upstream channel transmission will thus share the same window – 1,310 nm – while the OLT receiver will gain a new functionality, where it will have not only to assure proper power level adjustment via Automatic Gain Control (AGC) mechanism but it will also have to identify the incoming data rate and perform receiver adjustment in such a way to maximize its sensitivity for the particular burst. This is a non-trivial task and will require significant research to be carried out by electronics and receiver manufacturers. Initial results seem to indicate that such a solution is technically feasible though challenging, and thus it is expected that the first 10G EPON deployments will most likely operate in an asymmetric mode, with 10G downstream and 1G upstream channels.

The naming nomenclature for emerging symmetric 10G as well as mixed type 1G/10G EPON systems should follow the typical, IEEE naming convention. Legacy EPON systems were designated as 1000BASE-PX10/PX20, where P stands for

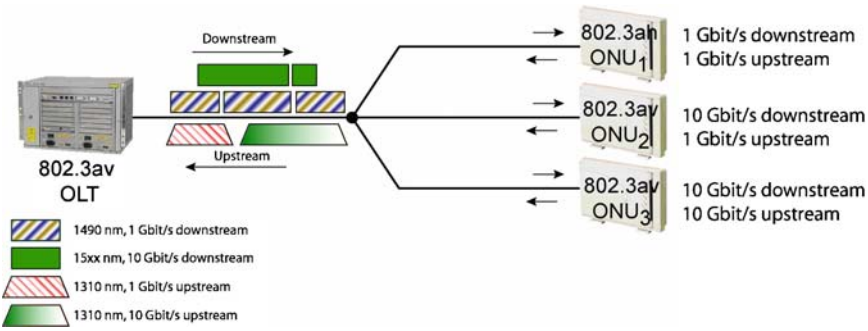

Fig. 2.22 1/10 Gbps downstream, 1/10 Gbps upstream (10/1GBASE-PRX system)

Passive Optical Networks and X indicates the employed channel coding (8B/10B), followed by the target system reach of 10 and 20 km, indicating what power budget the particular system supports. 10G EPONs will use different channel encoding (64B/66B), indicated by adding letter R in the port name e.g. 10GBASE-LR (L stands for long wavelength, 1,310 nm, no WIS (Wide area network Interface Sublayer) interface implemented) or 10GBASE-ER (E stands for extended band, 1,550 nm) – see IEEE 802.3 – 2005, clause 44 and the following ones. It is therefore a logical conclusion that the future 10G EPON ports will have to follow a similar naming style e.g. symmetric 10G EPON will be thus named 10GBASE-PR, indicating a PON structure with 64B/66B channel encoding for both downstream and upstream channels.

2.6.1.4 Migration from 1G to 10G EPON Systems

Phase 1 – Asymmetric 10G/1G Optical Network Units
in the System, Upgrade to Dual TX Rate Optical Line Terminal

The 10 Gbps EPONs will be introduced gradually into the currently existing EPON deployments. Initially available most likely only for the business customers, they will eventually find their way also to residential subscribers, providing that their manufacturing cost features the same decrease tendency as the one observed for legacy IEEE 802.3ah compliant equipment. However, this process will not lead to rapid adoption of symmetric 10G/10G EPONs, which are the final target of the said evolution. It is much easier to achieve the target 10 Gbps data rate in the downstream direction, using centrally located higher quality transmitter, operating in the 1,574–1,600 nm wavelength range. There is already 10 GE equipment operating with the mentioned data rate and with similar reach parameters, therefore the initial stages of the evolution path are most likely going to feature a dual data rate downstream and single data rate upstream channels, resulting in an asymmetric solution (see Fig. 2.22 for possible system schematic).

Another reason advocating in favour of this particular evolution step is the power budget of 10 Gbps EPONs where, due to the limited sensitivity of the burst-mode receiver which will be located in the OLT, higher power levels must be introduced into the fibre on the ONU side. Higher launch power will possibly require a larger, cooled Externally Modulated Laser (EML) and/or a post-amplification module, especially in the case of the highest 29 dB Channel Insertion Loss (CHIL). The exact location of the optical amplifier in this case is irrelevant at this point – most likely the transmitter manufacturers will take advantage of the cost reduction obtained by integrating the EML with a Semiconductor Optical Amplifier (SOA) in a single device, instead of constructing a discrete solution.

Despite the already existing technical feasibility of the first evolution phase, there are still a few technical hurdles which need to be overcome to assure successful migration from legacy 1 Gbps systems towards dual rate downstream channel EPONs. The OLT in such a configuration will have to operate with two independent MAC stacks for the downstream channel and a single one for the

upstream channel (IEEE 802.3ah compatible implementation running at the effective 1 Gbps data rate). At the same time, the MAC Client layer is presented with two interfaces with incompatible data rates i.e. one for the 10 Gbps downstream stack (unidirectional, since upstream channel is operated at 1 Gbps rate) and the other one which is bidirectional and operated in a manner consistent with the IEEE 802.3ah specifications.

Since both downstream channels can be operated independently, the two implemented MAC stacks will also have to be operated independently, thus requiring a new class of EPON chipsets, incorporating existing 1 Gbps solutions and integrating downstream 10 GE type P2P connection operating on P2M media, with more stringent power budget and modified Rx/Tx modules. Since a new development process will be required to produce such chipsets, it is expected that this particular phase will be transitory and will not affect a great number of customers. The upgrade costs at the later stages of deployment would invalidate the gain from introducing 10 Gbps channel for selected premium grade subscribers.

Phase 2 – Symmetric 10G/10G Optical Network Units in the System, Upgrade to Dual RX Rate Optical Line Terminal

At the second evolution phase of the transition process from 1 Gbps legacy systems towards fully symmetric 10 Gbps EPONs, the upstream channel receives the data rate upgrade for a number of selected subscribers. Again, since the equipment costs will be higher (at least for initial deployments) when compared with IEEE 802.3ah compliant products, it is most likely that only premium customers will be included in this program. Along with the progress in the transmitter technology, 10 Gbps directly modulated and most likely uncooled lasers will become available with parameters meeting the requirements of the upstream transmission in the 1,310 nm window [Gokhale07]. This should enable the EPON hardware manufacturers to introduce a cost effective 10 Gbps ONU module, capable of delivering symmetric data rate transmissions ten times faster than current legacy equipment. It is also possible that this particular phase is initiated faster, by deploying more expensive EML sources and thus increasing the possibility of reaching the critical mass required for wide adoption.

The technical hurdles at the second evolution stage include continuous operation in the dual rate environment, which requires state of the art equipment especially in the upstream direction. The unknown data rate of the arriving burst, coupled with the need to adjust the gain via an AGC module, imposes significant challenges in terms of electronic and optical interfaces, which are not capable of handling so highly different data rates at the moment. The initial, theoretical studies conduced by the Dual-Rate TF ad hoc formed by the IEEE 802.3av TF, indicate that it is possible to have such a system operating with minimum receiver sensitivity penalty for already deployed 1G ONUs. However, it was also indicated that the practical implementations may be far away, especially if the data rate detection is to be carried out completely at the PMD layer with no information obtained from the DBA agents

and MAC clients, which are the only entities in the system with the information about the data rate of the future scheduled bursts from individual ONUs.

Phase 3 – Gradual Removal of 1G Equipment from the Network

The last evolution stage in the transition path from 1G to symmetric 10G EPONs includes a gradual removal of the symmetric 1G IEEE 802.3ah compliant ONUs along with the replacement of asymmetric 10G/1G ONUs with the symmetric devices, providing that their manufacturing costs decrease with time, following the similar price reduction path which was observed for 1G EPON equipment. It is very difficult right now to predict whether the asymmetric IEEE 802.3av compliant equipment will be removed from the system altogether once deployed. Certain customer classes may require much higher downstream bandwidth than the upstream one, and thus asymmetric EPON equipment would serve their needs perfectly, while allowing for lower CAPEX for the SP. On the other hand, SPs may want to use only one ONU type in the network to minimize the stock and maintenance problems as well as take advantage of cheaper OLT cards, which would not need the dual rate operation. The pros and cons of both scenarios are very hard to evaluate at the moment, where even asymmetric 10/1G EPONs are still under early development and standardization stages.

2.6.2 Next Generation GPON Systems

The FSAN (Full Service Access Network) group is currently (January 2008) establishing the process of standardization of ngPONs, since the data rate as well as the number of channels are undefined at the moment. What is certain though is that the new ITU standard is poised to achieve higher data rates than ITU-T G.984 GPON [ITUG984] and IEEE 802.3–2005 EPON standards and also potentially increase the reach and the number of possible users on the P2M architecture. It is expected that the next generation series of ITU-T specifications will be based on the already existing service and stack models, while focusing mainly on the optimization of the delivery of Ethernet services, which represent a rapidly growing segment of provided connectivity services.

The next generation GPON system will have two main objectives, focusing on increasing the available bandwidth by a factor of 4 to achieve 10 Gbps (at least in the downstream direction) and ensuring that the new set of specifications is backwards compatible with the already installed GPON gear. The second requirement is obvious when considering the amount of GPON equipment deployed in the field in the next 2–4 years, during the process of developing the next generation standard.

The targeted increase in the channel capacity for both downstream and upstream directions has several options, which are currently under study in the FSAN group.

IEEE 802.3av TF chartered with the development of next generation EPON system opted for increasing the data rate to 10 Gbps while maintaining the number of channels unaltered i.e. using a dedicated wavelength for 10 Gbps data link in downstream and sharing the upstream channel with legacy 1 Gbps EPONs via TDMA. ngPON specification may however take advantage of the WDM, thus increasing the number of wavelength channels while maintaining the data rate relatively low (around 2.5 Gbps per wavelength) in order to avoid problems related with decreased sensitivity of photo detectors at 10 Gbps, dispersion penalties, etc. Such an approach has also the economic advantage of keeping the cost of user equipment relatively low, making use of the already existing subassemblies and packaging them into a single, larger module. The cost efficiency seems also to indicate that the four wavelength system would be the most technically and economically viable solution, since any larger number of data channels would require adoption of DWDM equipment with all the problems resulting from the required wavelength tracking, laser cooling and channel alignment.

One of the more interesting proposals for the ngPON access presented to FSAN for consideration originates from the FP6 project MUSE [Vetter05], as depicted in Fig. 2.23. Such network architecture, commonly referred to as Extra Large PON (XL-PON), can reach up to 512 subscribers located at the maximum of 100 km from the central office, thus effectively extending the reach of PON to five times its current typical distance. In this way, the service providers can deliver connectivity to rural and sparsely populated areas, as well as providing significant cost savings in urban environments, by eliminating the MAN network layer and interfacing directly to the core edge.

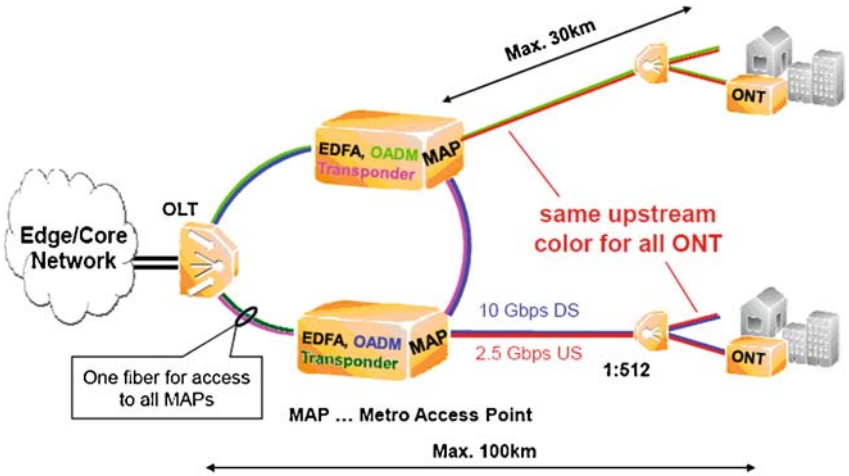

Fig. 2.23 A long reach PON system with the active Metro Access Point deployed in-field (FP6 project MUSE II)

The XL-PON effectively collapses therefore the access and metropolitan networks into a single, simplified network, allowing the service providers to make savings in terms of CAPEX (lower capital investment in equipment and deployment process) and OPEX (less equipment to manage, lower maintenance costs, etc.). However, due to the increased system reach as well as overall link budget in excess of 30 dB, the XL-PON has to employ optical amplification in both downstream and upstream channels, provided as one of the functions of the Metro Access Point (MAP) as depicted in Fig. 2.23. The MAP is then located at the local exchange, in place of the PON or DSL access equipment and houses a bidirectional erbium-doped fibre amplifier, adapted in such a way that it can cope with the signal power variations in the upstream channel due to the near-far effect, characteristic for PON deployments.

Additionally, the MAP unit is also responsible for wavelength conversion i.e. all the ONUs served with the XL-PON can operate at the same wavelength, resolving therefore instantly any problems with the tuneable or colourless transceivers, hurdling current WDM-PON deployments. A transceiver in the MAP receives the upstream data stream from the ONUs and relays it to the ring portion of the PON at the specific wavelength channel allocated for the given MAP. This way, the signal from the ONU is converted into the appropriate target wavelength channel and reaches the OLT receiver located approximately up to 100 km away. Such an extended functionality of MAP provides inherent protection against dispersion penalties in the long fibre section and minimizes the power budget problems, limiting the distance and/or split in the typical fully passive PON systems.

2.6.3 Summary

Next generation G/E-PON systems are expected to deliver much more bandwidth to the end-subscribers when compared with current legacy 1 Gbps equipment. They are capable of delivering more bandwidth capacity than CATV network using DOCSIS 3.0 protocol and other types of access, making them good candidate replacement architectures for next generation access networks. It will thus allow for significant increase in data bandwidth available to subscribers without forcing any drastic changes to the existing video&data distribution models employed by current operators, assuring that the currently deployed PON plants generate profit for years without painful required modifications.

Chapter 3
Components for Future Access Networks

Cristina Arellano, Carlos Bock, Karin Ennser, Jose A. Lazaro, Victor Polo, Bernhard Schrenk, and Stefano Taccheo

3.1 Tuneable Optical Network Unit

Due to the limited traffic generated by the Optical Network Unit (ONU), upstream Time Division Multiplexing (TDM) has been broadly accepted [Nakamura04] to optimize bandwidth allocation in Passive Optical Networks (PONs) as the ONUs are transmitting bursty at relative low bit rates. Multiplexing allows increasing the number of ONUs for each Optical Line Terminal (OLT) which is limited by the available number of wavelengths.

By taking into account that the requirements in time of business-customers and home-users can vary and, in order to improve bandwidth resources, the wavelengths must be dynamically allocable. ONUs provided with tuneable transceivers can give this flexibility. As ONUs should be cost effective, tuneable but cheap light sources such as white light sources with slow tuneable filters to transmit one wavelength bandwidth or cheap and slow tuneable laser sources as VCSELs (Vertical Cavity Surface Emitting Lasers) are interesting options.

Cost effective VCSEL laser, included as a sensor for consumer electronic devices like DVDs and PC mice, are increasing their number of applications, including 1,550 nm light sources for fibre optics communications. The industry is working with the idea of using VCSEL as a standard device for the PONs growth.

The advantages of VCSELs are well known: high efficiency, optical emission suited for many applications, high reliability and the ability of being powered with a battery. Single and multimode lasers are possible for telecommunications market. They are designed to address a wide variety of optical communication applications such as Gigabit Ethernet, Fibre Channel, SONET/SDH (Synchronous Optical Network/Synchronous Digital Hierarchy) and Coarse Wavelength Division Multiplexing (CWDM). The broadly acceptance of these lasers for the market would even produce, by mass production, a reduction in manufacturing cost in about 1 or 2 years.

The electronically tuneable VCSEL presents a 13 nm wide tuning range when using a 30 V tuning voltage, and a switching time of 200 μs [Yuen00] for C-band at 1,550 nm. Nowadays, the typical linewidth is about 30 MHz, and modulation bandwidths of up to 3 GHz at 2V operating voltages are possible.

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3.2 Fast-Tunable Laser at the Optical Line Terminal

As shown in previous chapters, centralized-control in terms of dynamic bandwidth allocation and also in terms of generation of all wavelengths in the PON is highly desirable for both: network performance and operator control. The advanced architectures perform agile WDM routing, which leads to a promising level of capacity and resource utilization efficiency combined with TDM. This is accomplished by means of new generation tuneable multi-electrode semiconductor lasers.

Novel designs of OLTs and DWDM (Dense Wavelength Division Multiplexing) PON ONUs can minimize the system cost considerably: first, tuneable lasers and receivers at the OLT are shared by all ONUs on the network to reduce the transceiver count and second, the fast tuneable lasers not only generate downstream data traffic but also provide DWDM PON ONUs with optical CW (Continuous Wave) bursts for their upstream data transmission. Stanford University Access architecture (SUCCESS) verifies that it can efficiently provide bidirectional transmission between the OLT and ONUs over multiple wavelengths with a small number of tuneable transmitters and receivers [An04].

The tuneable laser at the OLT can be used for both: agile WDM tuning and Frequency Shift Keying (FSK) modulation. At the ONU, an optical FSK detector to decode downstream data and an intensity modulator to encode upstream data are used. This new system configuration achieves the above mentioned characteristics.

The FSK modulation format allows the intensity remodulation of the signal at the ONU and is easy to generate with a tuneable laser, thus avoiding the use of an external modulator. Demodulation can be done by using an optical interferometer or a tuneable filter which is bit rate independent.

The Fibre-to-the-Home (FTTH) PON scheme is detailed in Fig. 3.1 [Prat05fsk], with the proposed design of the OLT and the ONU. For this network, an optical multiplexer is considered the best option for routing the signal to different ONUs. With this configuration several shared lasers at the OLT can be transmitting at the same time at different wavelengths.

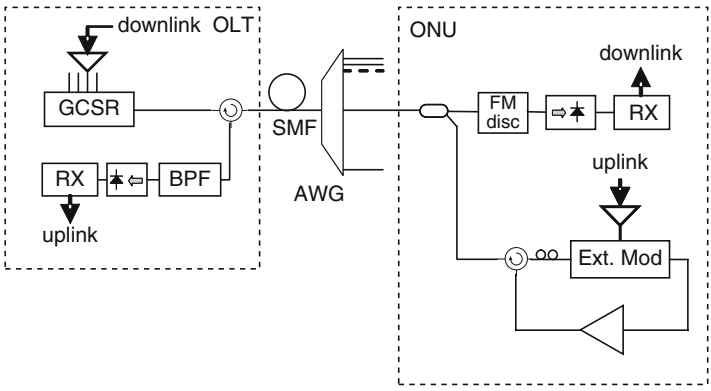


Fig. 3.1 Schematic of the Fibre-to-the-Home network

Due to fast tuning requirements, just electronic tuneable lasers are candidates to be used in access networks. A VCSEL is a cost effective device but its switching time of about 200 μs and its high electrical resistance require high currents and result in an important drawback. Distributed Feed-Back (DFB) lasers can be slow thermally tuned in a limited range, then not really interesting for this application Distributed Bragg Reflector (DBR) is discontinuous tuneable into the whole C-band and therefore not all wavelengths are available. Both SG-DBR (Sampled Grating-Distributed Bragg Reflector) and GCSR (Grating-assisted Coupler with Sampled Reflector) lasers are able to tune any standard ITU (International Telecommunication Union) channel in tens of nanoseconds, but SG-DBR needs relative high currents for driving and tuning which result in bigger thermal drifts than GCSR.

A tuneable laser, specifically a GCSR, was used to modulate the optical frequency of the downlink signal up to 1Gbps, directly modulating the Phase section current [Prat05fsk]. A previous equalizer has been implemented to extend the modulating bandwidth up to 600 MHz. The optical frequency deviation is 10 GHz, for a bias current of 500 μA.

In case of GCSR lasers, exploiting the free carrier plasma effect in the passive tuning region is not suited for high speed frequency modulation (FM) exceeding hundreds of megahertz, but it is fast enough for either low bit rate modulation in access networks or for wavelength switching applications.

Wavelength-agile OPS (Optical Packet Switching) systems require short tuning and settling time, low interference over neighbouring channels and low wavelength drift. For a GCSR laser is required the control of the wavelength switching characteristics if switching from short nanosecond to microsecond is required, as it is the case of OPS access applications. For example, state-of-art lasers suffer from fast mode hopping and undesirable counteracting slower thermal drifts of optical frequency toward a steady state value. In order to make feasible a successful control of its frequency derives, which are governed by thermal and carrier effects due to the current injection at switching, it is required the used of low driving currents for tuning.

Two techniques can be used to compensate the thermal effects on the optical frequency: first, a model based on the time constants of optical, electrical and thermal rate equations [Moeyersoon02], and second an auto-compensating model with distorted pulse current [Polo05].

Avoiding crosstalk interference during switching is possible either by using an external switch, by null transmission on the external intensity modulator or by switching the gain electrode of the laser to threshold [Polo05].

3.3 Arrayed Waveguide Gratings

Wavelength routers are another key component of future access networks. Wavelength routers can be divided into three categories depending on their application:

- Multiplexers
- Demultiplexers
- N × N router

Multiplexers are used to combine different wavelengths from different fibres into a single fibre, demultiplexers perform the opposite task: they separate incoming wavelengths from the input fibre to different fibres (Fig. 3.2). Finally, N × N routers perform both actions simultaneously and act as optical cross-connects.

To implement multiplexers, demultiplexers and routers one can use different techniques.

- Angular dispersion using prisms
- Concatenation of optical filters
- Arrayed-waveguide gratings
- Angular dispersion multiplexer
- Concatenation of multiplexer filters

We will focus in this section on Arrayed Waveguide Gratings (AWGs) because it is the technology which offers more benefits as AWG can be integrated thus its potential cost is low.

Figure 3.3 [Smit96] shows the schematic layout of an AWG. The operation is understood as follows. When the beam propagating through the transmitter waveguide enters the free propagation region (FPR) it is no longer laterally confined and becomes divergent. On arriving at the input aperture the beam is coupled into the waveguide array and propagates through the individual array waveguides to the output aperture. The length of the array waveguides is chosen such that the optical path length difference between adjacent waveguides equals an integer multiple of the central wavelength of the demultiplexer. For this wavelength the fields in the individual waveguides will arrive at the output aperture with equal phase (apart from an integer multiple of 2π) and the field distribution at the input aperture will be reproduced at the output aperture. The divergent beam at the input aperture is

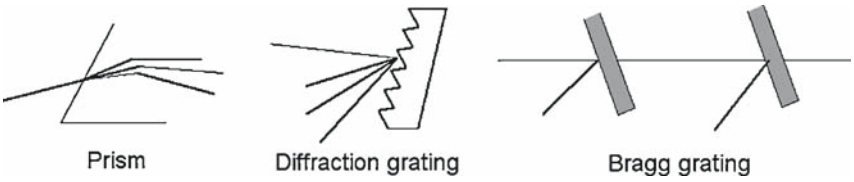


Fig. 3.2 Different wavelength routers

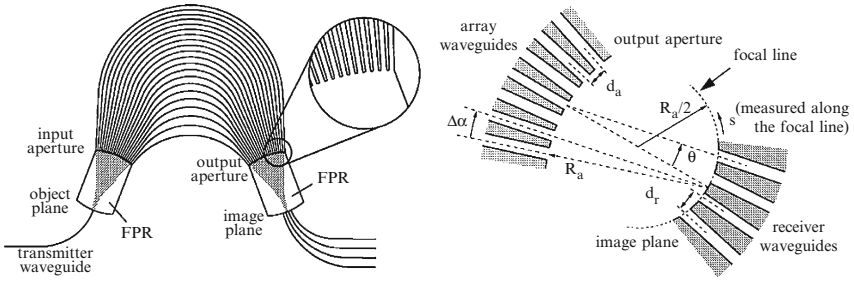


Fig. 3.3 Structure of an arrayed waveguide grating

thus transformed into a convergent one with equal amplitude and phase distribution, and an image of the input field at the object plane will be formed at the centre of the image plane. The dispersion of the AWG is due to the linearly increasing length of the array waveguides which will cause the phase change induced by a change in the wavelength to vary linearly along the output aperture. As a consequence, the outgoing beam will be tilted and the focal point will be shifted along the image plane. By placing receiver waveguides at proper positions along the image plane, spatial separation of the different wavelength channels is obtained.

The design of AWGs allows them to perform as multiplexers, demultiplexers and wavelength routers.

3.3.1 Wavelength Router Functionality

Wavelength routers were first reported by Dragone [Dragone91]. They provide an important additional functionality compared to multiplexers and demultiplexers and play a key role in more complex devices as add/drop multiplexers and wavelength switches. Figure 3.4 [Smit96] illustrates their functionality. Wavelength routers have *N* input and *N* output ports. Each of the *N* input ports can carry *N* different frequencies. The *N* frequencies carried by input channel 1 are distributed among output channels 1 to *N*, in such a way that output channel 1 carries frequency N and channel *N* frequency 1. The *N* frequencies carried by input 2 are distributed in the same way, but cyclically rotated by 1 channel in such a way that the

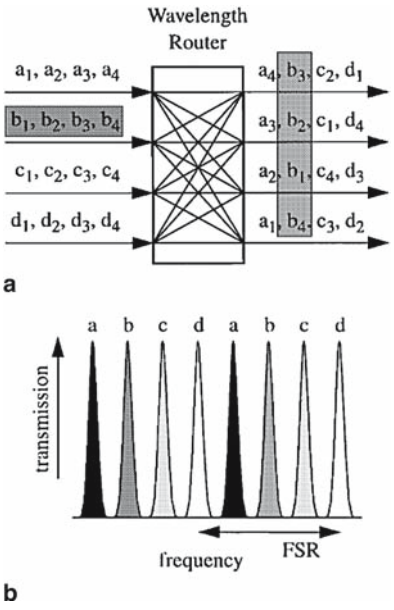


Fig. 3.4 Schematic diagram of the wavelength router operation; (a) interconnectivity scheme, and (b) frequency response

frequencies 1–3 are coupled to ports 3–1 and frequency 4 to port 4. In this way each output channel receives *N* different frequencies, one from each input channel. To realise such an interconnectivity scheme in a strictly nonblocking way using a single frequency a huge number of switches would be required. Using a wavelength router, this functionality can be achieved using only one single component.

A wavelength router is obtained by designing the input and the output side of an AWG symmetrically, i.e. with *N* input and *N* output ports. For the cyclical rotation of the input frequencies along the output ports, as described above, it is essential that the frequency response is periodical as shown in Fig. 3.4b, which implies that the FSR should equal N times the channel spacing.

3.3.2 Applications in Access Networks

The typical application of AWGs in access is to deploy a combined WDM/TDM PON, having a feeder fibre along which several WDM channels are transmitted and then an AWG to separate each channel and distribute it on a classical TDM PON topology (Fig. 3.5).

However, N × N AWGs have many applications in access due to the cyclical periodicity of their routing profile. In [Bock06] it is presented an advanced dynamic bandwidth allocation algorithm that uses an N × N AWG to avoid correlation among traffic sources. Further explanations about applications of N × N AWGs in access are described in [Bock04], [Bock05] and [Tsalamanis04].

3.3.3 Arrayed Waveguide Grating Characterization

The main parameters characterizing the performance of AWGs are:

- Insertion losses
- The H(f) response type (Gaussian or flatted)

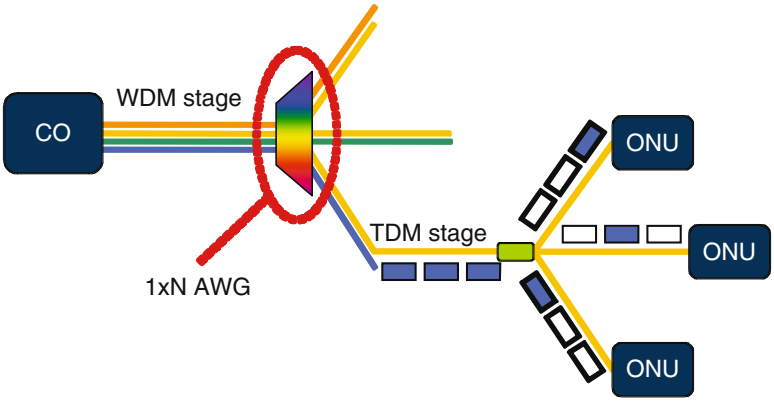


Fig. 3.5 Arrayed Waveguide Grating in a WDM/TDM PON approach

- The wavelength plan of each output port
- Number of free spectral ranges (FSR)
- Thermal stability

Figure 3.6 presents the response of a 1 × 40 AWG.

Channels were chosen to be ITU-T grid compliant [ITUG694.1] and the maximum drifts were measured to be 0.02 nm. The response was Gaussian and insertion losses were between 7.7 and 6.4 dB. No FSR were recorded as the AWG encapsulation had a pre-filtering stage that suppressed any wavelength out of the AWG main FSR range. Further parameters are detailed in the Table 3.1.

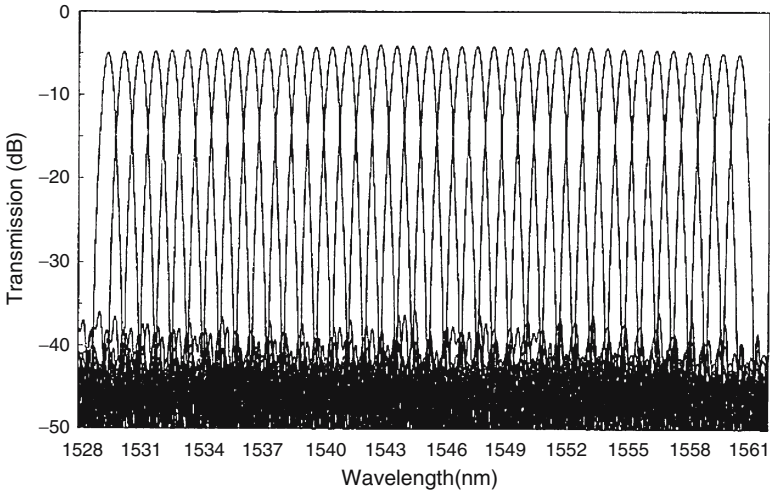


Fig. 3.6 1 × 40 arrayed waveguide grating channels

Table 3.1 1 × 40 arrayed waveguide grating specifications

Parameter	Spec	Units
Channels	40	Ch
Channel spacing	100	GHz
ITU frequency	196.0–192.1	THz
Center wavelength accuracy	−0.035 .. +0.035	nm
Reference passband	−12.5 .. +12.5	GHz
Insertion loss	7.0	dB
Insertion loss uniformity	1	dB
Ripple	0.4	dB
PDL	0.3	dB
0.5 dB bandwidth	0.25	nm
1 dB bandwidth	0.4	nm
3 dB bandwidth	0.55	nm
Adjacent channel isolation	26	dB
Non-adjacent channel isolation	33	dB
Total crosstalk	23	dB
Return loss	45	dB
Chromatic dispersion	−10 .. 10	ps/nm
Polarization mode dispersion	0.5	ps

Table 3.2 8 × 8 arrayed waveguide grating routing matrix

I/O	1	2	3	4	5	6	7	8
1						1589.02 4.03dB 2.8	1584.68 5.15dB 2.8	1580.9 6.04dB 2.8
2					1588.88 3.72dB 2.52	1584.82 3.86dB 3	1580.76 4.78dB 2.8	1576.98 5.57dB 2.52
3				1588.88 3.39dB 2.52	1584.96 3.19dB 2.8	1580.9 3.53dB 2.8	1576.7 4.29dB 2.8	1572.92 5.21dB 2.8
4			1588.88 2.76dB 2.52	1584.96 2.54dB 2.8	1580.9 2.88dB 2.8	1576.98 3.14dB 2.52	1572.78 3.76dB 2.52	1568.86 4.52dB 2.8
5		1588.88 3.68dB 2.52	1584.96 3.05dB 2.8	1580.9 3.28dB 2.8	1576.98 3.32dB 2.52	1572.78 3.28dB 2.8	1568.72 3.76dB 2.8	1564.94 4.56dB 2.52
6	1589.02 4.65dB 2.8	1584.96 3.84dB 2.8	1580.9 3.28dB 2.8	1576.98 3.21dB 2.52	1572.78 3.11dB 3	1568.72 3.00dB 2.8	1564.66 3.49dB 2.8	1560.74 4.41dB 3
7	1584.82 5.75dB 2.8	1580.76 5.11dB 2.8	1576.84 4.26dB 2.52	1572.64 3.76dB 2.8	1568.72 3.8dB 2.8	1564.66 3.88dB 2.8	1560.6 5.01dB 2.8	1556.68 5.79dB 2.8
8	1581.04 6.63dB 2.52	1576.84 5.79dB 2.8	1572.78 4.95dB 2.8	1568.86 4.29dB 2.8	1564.80 4.54dB 2.8	1560.74 4.95dB 2.8	1556.82 5.79dB 2.52	1552.9 6.26dB 2.52
1	1575.86 6.96dB 2.8	1571.94 4.88dB 2.8	1568.02 4.46 2.8	1564.1 3.71dB 2.8	1560.18 3.97dB 2.8	1556.26 3.45dB 2.52	1552.34 4.27dB 2.52	1548.56 4.97dB 2.52
2	1572.08 5.61dB 2.8	1568.16 4.46dB 2.52	1564.24 3.77dB 2.52	1560.32 3.39dB 2.52	1556.4 3.6dB 2.52	1552.34 3.71dB 2.8	1548.28 4.74dB 2.8	1544.64 5.58dB 2.52
3	1568.16 5.2dB 2.52	1564.1 3.78dB 2.8	1560.32 3.15dB 2.52	1556.26 3.05dB 2.8	1552.34 3.39dB 2.8	1548.42 3.65dB 2.8	1544.36 4.29dB 2.8	1540.58 4.85dB 2.8
4	1564.1 4.25dB 2.8	1560.18 3.28dB 2.8	1556.26 2.71dB 2.8	1552.43 2.66dB 2.8	1548.42 3.15dB 2.8	1544.36 3.11dB 2.8	1540.44 3.44dB 2.52	1536.66 4.4dB 2.8
5	1560.32 4.52dB 2.52	1556.4 3.79dB 2.52	1552.34 3.28dB 2.8	1548.42 3.41dB 2.8	1544.5 3.34dB 2.52	1540.58 2.9dB 2.52	1536.52 3.78dB 2.8	1532.74 4.57dB 2.8
6	1556.26 4.86dB 2.8	1552.34 3.96dB 2.8	1548.42 3.28dB 2.8	1544.5 3.17dB 2.52	1540.58 2.87dB 2.52	1536.52 3.03dB 2.8	1532.6 3.42dB 2.52	1528.82 4.88dB 2.8
7	1552.2 5.77dB 2.8	1548.28 4.9dB 2.8	1544.36 4.34dB 2.8	1540.3 4.00dB 2.8	1536.52 3.97dB 2.52	1532.46 3.77dB 2.8	1528.68 5.16dB 2.52	1524.76 6.83dB 2.8
8	1548.56 6.36dB 2.52	1544.64 5.77dB 2.52	1540.58 5.22dB 2.8	1536.52 4.42dB 2.8	1532.74 4.24dB 2.52	1528.82 4.86dB 2.8	1524.9 6.78dB 2.52	1520.7 7.62dB 2.52
1	1544.22 6.36dB 2.24	1540.3 4.72dB 2.8	1536.66 4.43dB 2.24	1532.74 3.66dB 2.52	1528.96 4.1dB 2.52	1525.04 4.6dB 2.52	1521.12 6.15dB 2.52	
2	1540.4 5.72dB 2.52	1536.66 4.59dB 2.52	1532.74 3.83dB 2.52	1528.82 3.6dB 2.8	1525.18 4.25dB 2.52	1521.26 4.51dB 2.52		
3	1536.66 5.04dB 2.52	1532.74 3.71dB 2.52	1528.96 3.58dB 2.52	1525.04 3.88dB 2.8	1521.12 4.51dB 2.8			
4	1532.74 4.2dB 2.52	1528.82 3.62dB 2.8	1525.04 3.51dB 2.8	1520.98 3.68dB 2.8				
5	1528.96 4.8dB 2.52	1525.18 4.48dB 2.52	1521.26 4.24dB 2.52		FSR≈32.5 nM Δf≈2.66nM Finesse=12.22			
6	1525.04 5.22dB 2.8	1521.12 4.47dB 2.8						
7	1521.12 6.95dB 2.52			Legend->	λ(nm) IL(dB)Δf(nm)			
8								

Further to the parameters described above, N × N AWGs require the specification of the routing matrix. Table 3.2 presents the routing matrix of an 8 × 8 AWG. N × N AWGs are very rare devices, which are not commercially distributed but just produced as custom designs. Typically, they do not have any pre-filter so FSRs can be clearly measured. This is presented in Fig. 3.7.

The 8 × 8 AWG characteristics exposed as example in Table 3.2 and Fig. 3.7 shows insertion losses between 5.16 and 2.71 dB in a Gaussian profile, with a 3 dB passband of 2.52–2.8 nm, depending on the channel and a FSR of 32.5 nm.

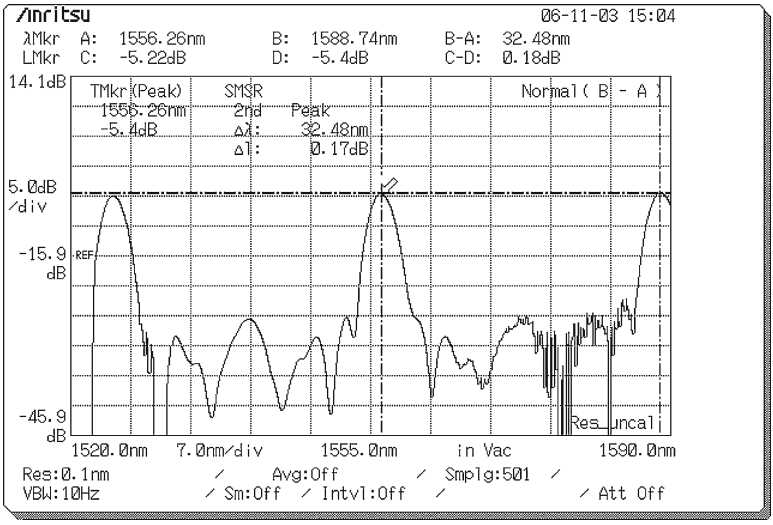


Fig. 3.7 8 × 8 arrayed waveguide grating free spectral range

3.4 Reflective Receivers and Modulators

At present, there is always a laser diode at the ONU side in commercial implementations to send the upstream data. This is a good approach for single wavelength PONs as there is just one wavelength used for upstream transmission and VCSELs which are very cheap can be used. However, when WDM PONs are deployed, a wavelength-specific emitter is needed. The use of wavelength-specific lasers for each ONU is not manageable due to its huge stock problems as each ONU of the WDM PON would need different equipment.

To solve this, there are two approaches:

- To use a tuneable source. This option is under study at present although the cost of tuneable sources is high at the moment. However, it is a future option if cost effective tuneable lasers can be designed.
- To use an optical modulator or a reflective device at the ONU and send the optical carrier from the Central Office (CO). This option is very interesting from the research point of view because it opens a wide range of possibilities. However, there is no commercial product with these features as it is not cost effective at present.

An optical modulator is a device that allows manipulating a property of light (typically a laser beam). Depending on which property of light is controlled, one talks about intensity modulators, phase modulators, polarization modulators, etc.

Optical modulators can be divided in the following categories:

- Acousto-optic modulators, used for switching or continuously adjusting the amplitude of a laser beam, for shifting its optical frequency or its spatial direction
- Electro-optic modulators, used for modifying the polarization, phase or power of a beam as well as for pulse generation in the context of ultrashort pulse amplifiers
- Electroabsorption modulators, used for transmitters in optical fibre communications
- Interferometric modulators, e.g. Mach-Zehnder modulators, often realised in integrated optical circuits and used in optical data transmission
- Liquid crystal modulators, used e.g. in optical displays and in pulse shapers, often used as spatial light modulators, i.e. with a spatially varying modulation
- Chopper wheels for periodically switching or modulating the power of a light beam
- Fibre-optic modulators, often available as fibre pig-tailed bulk components
- Micromechanical modulators (which are micro electro-mechanical systems, MEMS), e.g. silicon-based light valves and two-dimensional mirror arrays

This section will analyze ElectroAbsorption Modulators (EAM), SOAs and reflective SOAs (RSOAs) as they offer very good specifications for being used as wavelength-agnostic ONUs.

SOAs and RSOAs are formal not modulators but can be used as modulators by controlling their bias current and thus their amplification. All of them are suitable for integration which means that their potential cost is low. Furthermore, EAMs can be modulated at high data rates. SOAs and RSOAs cannot provide so high modulation bandwidth as EAMs, but offer amplification capabilities.

3.4.1 Electroabsorption Modulator

An EAM is a semiconductor device that allows controlling the intensity of a laser beam via an electric voltage (Fig. 3.8). Its operation principle is based on the Franz-Keldysh effect: a change of the absorption spectrum caused by an applied electric field, which usually does not involve the excitation of carriers by the electric field.

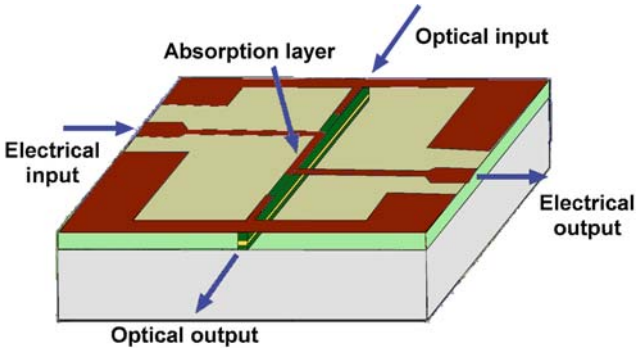


Fig. 3.8 Electroabsorption modulator

Most electroabsorption modulators are made in the form of a waveguide with electrodes for applying an electric field in a direction perpendicular to the modulated light beam. For achieving a high extinction ratio, one usually exploits the quantum confined Stark effect in a quantum well structure.

Compared with electro-optic modulators, electroabsorption modulators can operate with much lower voltages (a few volts instead of hundreds or thousands of volts). They can be operated at very high speed; a modulation bandwidth of tens of gigahertz can be achieved which makes these devices useful for optical fibre communications. A convenient feature is that an electroabsorption modulator can be integrated with a distributed feedback laser diode on a single chip to form a data transmitter in the form of a photonic integrated circuit. Compared with directly modulating the laser diode, one can obtain a higher bandwidth and reduced chirp in this way.

3.4.2 Semiconductor Optical Amplifiers

Semiconductor optical amplifiers (SOAs) have a similar structure as Fabry-Perot laser diodes but they are designed with anti-reflection elements at the endfaces (Fig. 3.9). Recent designs include anti-reflective coatings and tilted waveguide and window regions to eliminate endface reflection almost perfectly. This effectively prevents the amplifier from acting as a laser.

The semiconductor optical amplifier is of small size and electrically pumped. It can be potentially less expensive than the Erbium Doped Fibre Amplifier (EDFA) and can be integrated with semiconductor lasers, modulators, etc. However, the performance is still not comparable with the EDFA. The SOA has higher noise, lower gain, moderate polarization dependence and high nonlinearity with fast transient time. This nonlinearity presents the most severe problem for optical communication applications.

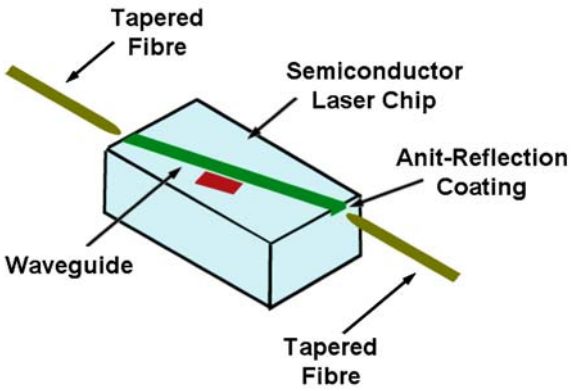


Fig. 3.9 Semiconductor optical amplifier

High optical nonlinearity makes semiconductor amplifiers attractive for all-optical signal processing like all-optical switching and wavelength conversion. There has been much research on semiconductor optical amplifiers to use them as components for optical computation.

3.4.3 Reflective Semiconductor Optical Amplifier

The RSOA [Prat05r] consists of a conventional SOA in combination with a rear facet mirror such that the amplified lightwave is retro-reflected (Fig. 3.10). This characteristic provides an increased gain from the device due to the double pass of the light through the gain region. An additional characteristic is their ability to modulate the incoming signal, removing the need for a local light source.

3.4.3.1 RSOA Characterization

RSOA response depends on the incoming signal power and the bias current that is injected to the device. Figure 3.11 presents the output power of an RSOA that has been characterized in our labs.

From Fig. 3.11 it can be seen that the RSOA has different performance regions which are the linear and the saturation response region. The linear region is preferred to use the RSOA as a modulator, as offers the highest extinction ratio. On the other hand, the saturation region is preferred when RSOA performs as a photo receiver. If the RSOA needs to be used as both, modulator and photo receiver [Prat05r], a compromise should be met to achieve correct performance on both tasks.

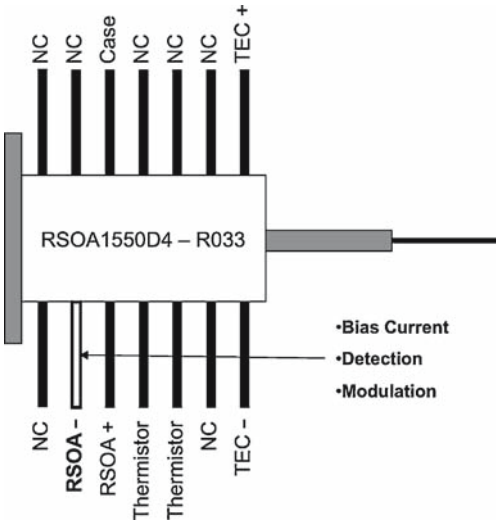


Fig. 3.10 Reflective semiconductor optical amplifier

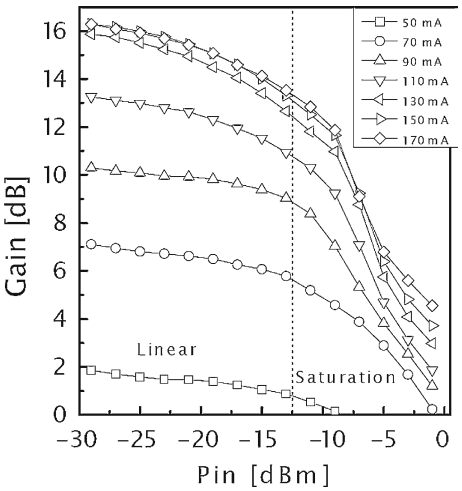


Fig. 3.11 Response of a reflective semiconductor optical amplifier for several bias currents

3.4.3.2 Applications in Access Networks

The use of reflective modulation techniques with RSOAs and EAMs is gaining attention in access due to the evolution of WDM PONs. As mentioned in the introduction, in WDM PON systems each ONU requires a specific wavelength for upstream transmission and the use of wavelength-specific sources is not viable due to stock problems.

The use of an RSOA, a combination of SOA + REAM (Reflective EAM) or in general a modulator to transmit upstream by modulating an optical carrier sent from the CO [Kang06], [Prat05a], [Takesue06] allows the design of wavelength-agnostic ONUs, which is the most relevant application of SOAs and EAMs in access at present.

3.4.4 Erbium Doped Waveguide Amplifiers and Integration with RSOA and REAM for High Performance Colourless ONT

As it has been commented in previous sections, RSOAs have been proposed as cost effective solutions [Prat05a] and also recently, higher performance Optical Network Terminal (ONT) equipment based on REAMs has been investigated [Garreau06], [Kazmierski07]. The RSOA provides very useful optical amplification to compensate link losses and provide enough power for upstream data. However, we have tested that available RSOAs offer limited gain and, as the gain increases, the RSOA bandwidth decreases and thus limits the available bit rate of the link.

At Fig. 3.12, it can be seen that for a low signal level in the order of −25 dBm the RSOA can provide an output power close to −3 dBm but only a strongly limited modulation bandwidth. This is another issue of this device: the modulation bandwidth strongly depends on the optical input power and the bias current. As shown in Fig. 3.13, it may range from 0.6 GHz to 1.25 GHz.

On the other hand, the application of colourless ONT to access networks demands from those devices that they suit to the link specifications of the currently under deployment Gigabit Passive Optical Network (GPON) [G.984.2] and Ethernet Passive Optical Network (EPON) [IEEE802.3ah] standards. As shown in Fig. 3.14, several link attenuations are defined by the current GPON, establishing tree network classes (A, B and C) for corresponding link attenuations. Also the minimum ONT-RX received power levels, averaged minimum ONT-TX power and

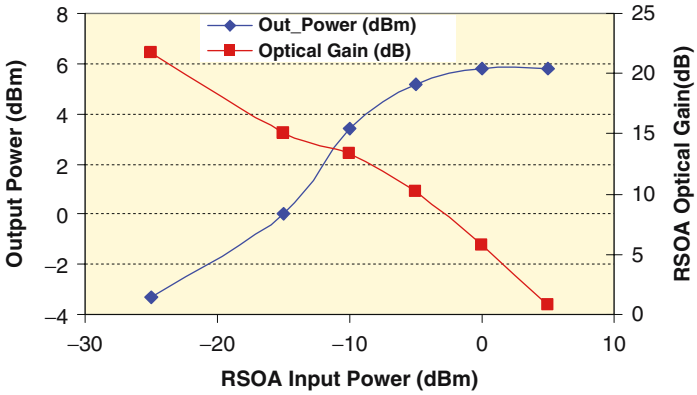


Fig. 3.12 Optical gain and output power of a reflective semiconductor optical amplifier that is operated at 20°C, 80 mA, 1,550 nm for several input signal power values

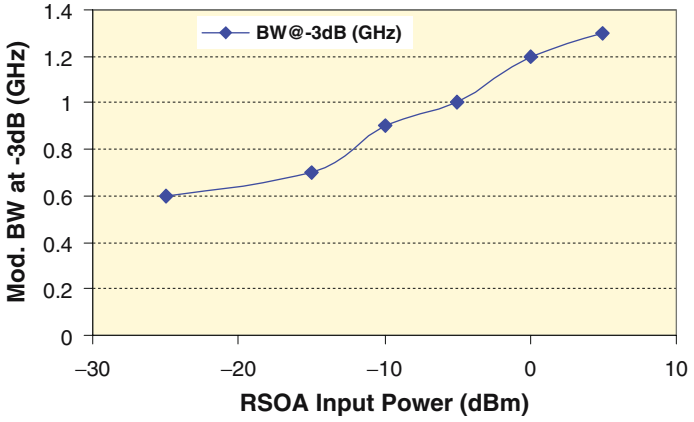
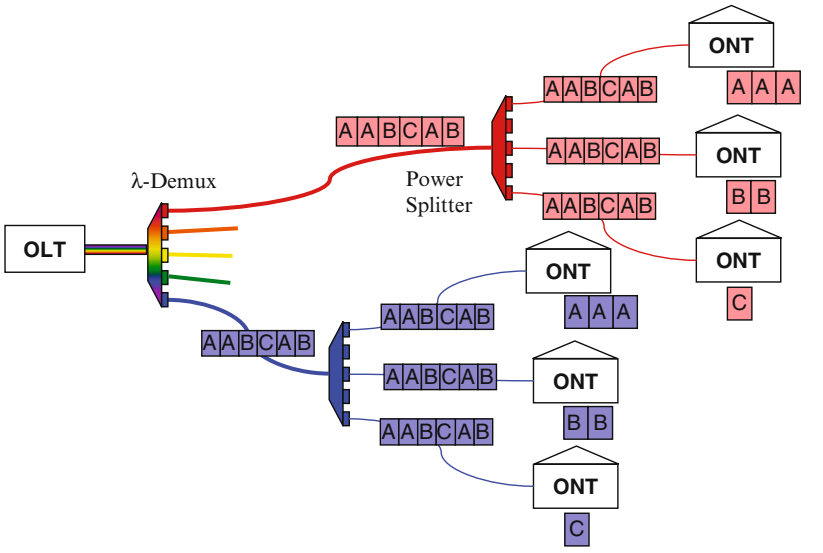


Fig. 3.13 Modulation bandwidth of a reflective semiconductor optical amplifier that is operated at 20°C, 80 mA, 1,550 nm for several input signal power values



Link attenuation (dB)		
Class	Min	Max
A	5	20
B	10	25
C	15	30

ONT-TX avg. Power (dBm)		
Class	Min	Max
A	–3	2
B	–2	3
C	2	7

ONT-RX Min receiver power	
Class	Sensitivity
A	–24
B	–28
C	–29

- G.984.2 (03/2003)

Fig. 3.14 RSOA's TDM PON including the GPON ITU-T specifications (G.984.2) for link attenuation, ONT's launched power and sensitivity at 1.25 Gbps

maximum launch power values for GPON at 1244.16 Mbps are shown. EPON recommendations [IEEE802.3ah] are less demanding than those from GPON.

Next generation WDM and WDM/TDM based PONs using wavelength-agnostic sources could be standardized for other network characteristics in future (e.g. longer distances, higher splitting ratios, another wavelength allocation), but most probably is that migration requirements will force the wavelength-agnostic sources to cope with these already standardized requirements.

As it can be seen from Figs. 3.12 and 3.13, commercially available RSOAs do not fulfil the required performance. A possible alternative is to use an Erbium-doped optical amplifier (OA) as gain element, providing high bidirectional gain and excellent noise figure. However due to the typical burst mode upstream signals in PONs, gain stability is also required. In addition, the cost issue associated with ONT will require low cost OA with mass production that is not compatible with fibre OA. Erbium-Doped Waveguide Amplifiers (EDWA) have demonstrated to offer excellent gain stabilisation properties [Ennser06], high gain, bidirectional operation [DellaValle06] and insensitivity to burst transmission [Taccheo07]. PON specifications are still quite peculiar and pose further challenges.

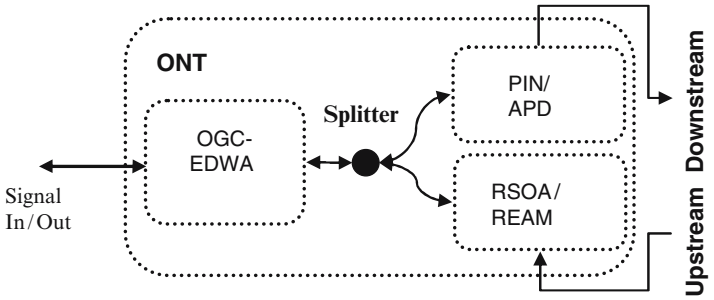


Fig. 3.15 Equipment of an Optical Network Terminal including an Erbium Doped Waveguide Amplifier

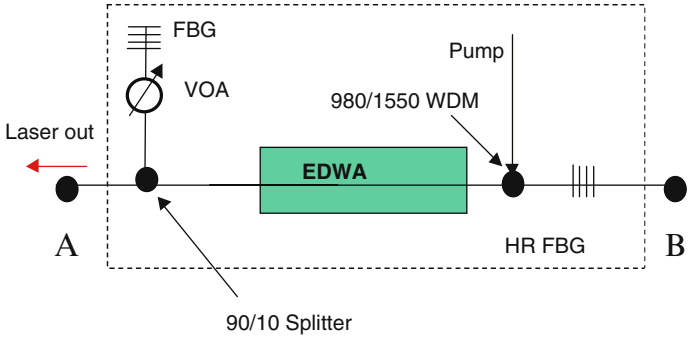


Fig. 3.16 Gain-stabilised bidirectional Erbium Doped Waveguide Amplifier schematic

The integration of EDWA with RSOA or REAM is depicted in Fig. 3.15. The EDWA can provide gain capacities to accomplish and overcome current GPON and EPON recommendations and provides a path for upgrading next generation PONs to 10 Gbps if REAM or enhanced RSOA are used.

Figure 3.16 shows the schematic setup of a gain-stabilised EDWA [Ennser06]. Gain stabilisation is provided by the optical gain clamping (OGC) technique where the EDWA becomes the gain medium of a laser and the feedback is provided by two Fibre Bragg Gratings (FBG). The Variable Optical Attenuator (VOA) allows tuning the amplifier gain dynamically. The lasing action at 1,550 nm is determined by the FBGs. A 95%/5% power splitter is used and the cavity loss is adjusted to 20 dB by adjusting the Variable optical Attenuator (VOA).

The OGC-EDWA is adjusted to provide a gain of 20 dB across the full C-band. It is also assumed that the input power may vary from −28 to −10 dBm for downstream and output power has to be 0 dBm for upstream (e.g. class B).

The division ratio of the second splitter in Fig. 3.15 can be used to accommodate PIN/APD and RSOA/REAM characteristics. For example, by using a 75/25 splitter, minimum signal levels of −10 and −15 dBm to the detector and remodulator can be

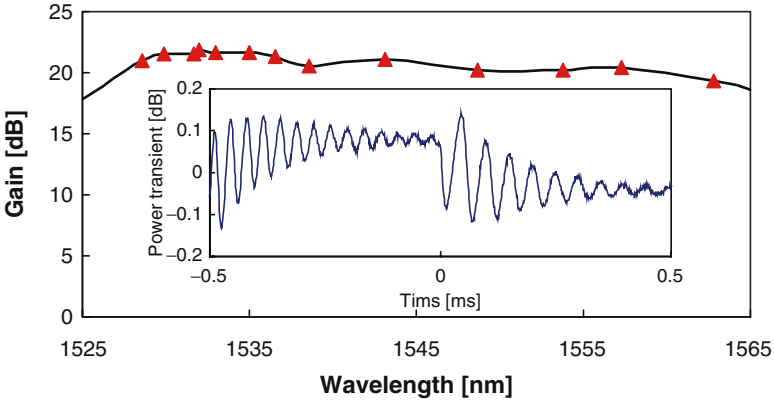


Fig. 3.17 Gain curve for an input power of 10 dBm, and the power transient of downstream signal induced by the leading and trailing edge of the upstream burst

provided. In this case, a lower sensitivity and more cost effective PIN and also a commercially available RSOA can be used [Lazaro07c]. Other splitting values allow either to use gainless modulators as a REAM or to provide outperforming output power values in the range of 10 dBm.

The experimental results in Fig. 3.17 shows the clamped EDWA gain for an input power of −10 dBm and pump power of 225 mW at 980 nm. It is described here a prototype under investigation, so its length is not exactly optimized for 20 dB gain and a slightly difference of 1.5 dB is seen. A flatter gain curve can be obtained with optimised samples. The noise figure is 6–6.5 dB across the full C-band. To evaluate the downstream gain transient (λ_{down} = 1,555 nm) induced by upstream signal burst (λ_{up} = 1,537 nm), a square waveform signal (500 µs period, −5 dBm maximum power) was used. The inset in Fig. 3.17 shows the resulting gain transient with less than 0.2 dB peak-to-peak ripple.

Chapter 4
Enhanced Transmission Techniques

Paulo André, Cristina Arellano, Carlos Bock, Francesc Bonada, Philippe Chanclou, Josep M. Fàbrega, Naveena Genay, Ton Koonen, Jose A. Lazaro, Jason Lepley, Eduardo T. López, Mireia Omella, Victor Polo, Josep Prat, Antonio Teixeira, Silvia Di Bartolo, Giorgio Tosi Beleffi, and Stuart D. Walker

Next generation Passive Optical Networks (ngPONs) that offer increased bandwidth and distance-reach to a higher number of customers may require some modifications in the network infrastructure and in the technology of its devices. Nevertheless, these changes should not require a significant increased cost nor upgrading complexity.

Optical Network Units (ONUs) at customer premises of currently deployed PONs include a fixed laser at a non-controlled wavelength, launching the light into the upstream fibre or into a single fibre via a coarse WDM multiplexer. In future PONs, Wavelength division multiplexing (WDM) can be effectively used to upgrade the overall PON capacity in several ways. Thus, new generation ONUs may be wavelength-controlled, wavelength-tuneable or wavelength-agnostic.

WDM allows superposing different TDMA PONs over the access fibre line. The number of wavelengths then corresponds to two times the number of TDMA PON systems. This solution offers desirable characteristics for an access infrastructure as the use of one single fibre for both upstream and downstream transmission reduces the network size and connection complexity.

Another WDM scenario is to allocate one wavelength to one user, by using wavelength division multiple access (WDMA). The number of wavelengths corresponds to the number of users.

Other key desirable characteristics of a WDM(A) access optical network are the elimination of the laser source at the ONU and wavelength independence to fit a transparent user interface. Different scenarios exist to perform this called 'colourless' property:

- Spectrum slicing: this solution uses a broadband spectrum optical light source at each ONU. The signals are spectrally sliced by a wavelength filter.
- Wavelength supply: in this option no light source is employed at the ONU. The optical carriers are supplied from the central office to the ONUs.
- Tuneable light source: it consists of a tuneable light source at the ONU.
- Remodulation: in this approach the same optical signal is used for upstream and downstream. Different solutions are advanced to achieve this bidirectionality (performance limited by Rayleigh backscattering) as combined phase-shift keying/ intermediate modulation, electroabsorption remodulation, polarization rotation modulator and remodulation using semiconductor optical amplifier (SOA). This technique is

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ideally suited for single fibre bidirectional transmission, leading to important savings in the external fibre plant and in the Customer Premises Equipment (CPE).

Other physical layer issues that can be relevant for next generation PONs are also included: optical amplification in the PON, or controllable splitting ratio, protection devices, new modulation formats, wavelength conversion, tuneable lasers for PONs, radio-over-fibre systems, etc. These are key enabling techniques for the future growth of PON performances and functionalities.

4.1 Advanced Functionalities in PONs

In the last years the attention has been focused on the access network due to several reasons like the devolvement of high speed Internet traffic and broadband multimedia services [Kramer01]. Another driver in this crucial market sector has been the birth of new service providers interested in building their own access network to offer their services. Their attention is focused on equipment costs and potential fast revenues in order to reach the break event point in the fastest way. For these reasons, PON topologies are driving the attention as emerging technologies with key characteristics like scalability, high bandwidth, low implementation costs and capacity of delivering every service to several end-users over a single network [Lee06], [Tran06]. The PON topologies can be developed with several and different shapes like bus, tree, bus plus tree or ring. As mentioned in previous chapters, a typical tree topology is composed by an Optical Line Termination (OLT) working at 1,490 nm to broadcast the downstream signal, and several ONUs at the subscribers side are working at 1,300 nm window for the upstream signal.

It is well known that in the metro network and especially in the transport network segment, the introduction of WDM permitted to increase the available capacity of several order of magnitudes without increasing the costs with the same data rate. In fact, the industrial maturity lowered the costs of transmitters, flat amplifiers and high speed receivers allowing the possibility to send on the same fibre several tens of different wavelengths maintaining a control on the per-bit-cost. In this scenario the possibility to merge the WDM world with the Passive Optical Network (PON) world is starting to attract the attention of the investors considering the tremendous possibilities given to increase, virtually without end, the scalability and the flexibility of the cost effective PON networks.

4.1.1 Wavelength Conversion

In this subchapter we demonstrate the possibility to convert the PON downstream signal at 1,490 nm to a C-band signal and then to convert it back into its usual operative band (1,480–1,500 nm, according to 802.3ah), based both on a SOA

double XGM (Cross Gain Modulation) and a single XGM plus noise modulation. This function permits to develop WDM EPON and to realise wavelength routing for granting several service providers to share the same physical access network. Moreover, it grants the possibility of treating the signal in the C-band, in which the majority of low cost devices like distributed feedback lasers (DFB) and erbium doped fibre amplifiers (EDFA) work.

The experimental setup is reported in Fig. 4.1. The signal from the OLT (AN5116-03 ePON FiberHome) is coupled with a continuous wave (CW) from a DFB laser. These signals enter the first SOA (Covega 2385) where the first wavelength conversion based on a standard cross gain modulation (XGM) takes place. The OLT provides two Gigabit Ethernet ports (EPON1 and EPON2) and is therefore able to implement two different passive optical networks. The XGM1 converts the OLT wavelength from 1,490 to 1,536 nm close to the SOA gain peak. The converted signal is subsequently coupled with a second CW from an external cavity laser (ECL). These signals enter the second SOA (Alcatel M18) that performs the subsequent second XGM.

In XGM1 the signal is logically inverted, in XGM2 there is a second logical inversion that brings the signal back to its original shape (Fig. 4.2). The results reported in Figs. 4.2 and 4.3 were taken using a real time oscilloscope (Tektronix DSA 602). The double XGM induces a contextual decrease in the signal quality but the total worsening does not avoid the communication between OLT and ONUs (AN5006-05 ePON FiberHome).

A second method that guarantees optical wavelength conversion is based on the modulation and subsequent filtering of the Amplified Spontaneous Emission (ASE) SOA spectrum as reported in Fig. 4.3. Downstream and upstream have different lengths (e.g. downlink is about 89 m, uplink about 31 m) but the system still works

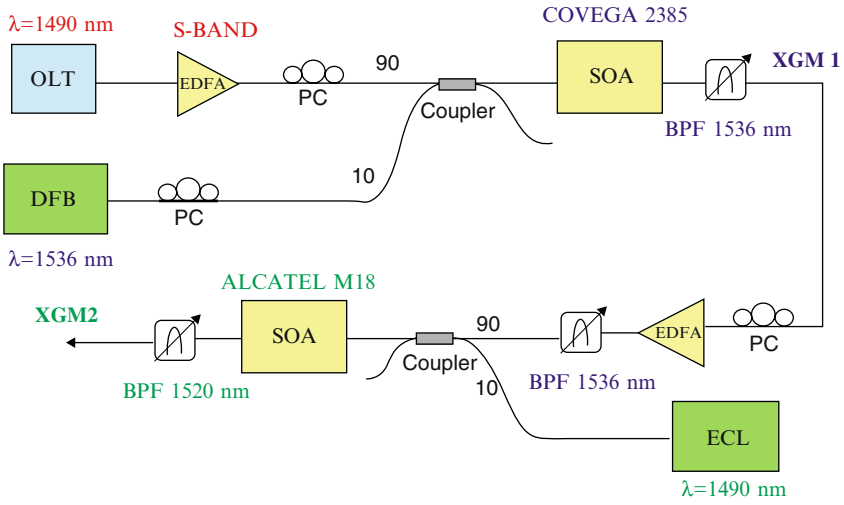

Fig. 4.1 Experimental setup used to demonstrate the wavelength conversion

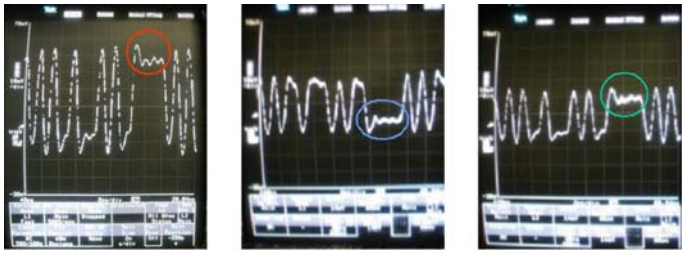

Fig. 4.2 Signal conversions with double cross gain modulation

Fig. 4.3 Signal conversions with noise modulation and single cross gain modulation

normally and the performance is similar to the back-to-back case. The power operational range for the ONU is between −5 and −20 dBm.

The noise modulation setup is similar to Fig. 4.1. The difference is the absence of the DFB branch, so the amplified OLT enters the SOA saturating its gain. The performance gets worse because the digital signal on the high level is much noisier. However, the second conversion reconverts and cleans the signal. In the end, ONUs and OLT still exchange packets but with a worsening in the performance.

Figure 4.4b shows measured throughput (using Ixia Chariot program) at 1,490 nm during a test performed between two PCs connected to the EPON1 and to the EPON2 like reported in Fig. 4.4a. In the first bar, the signal of EPON1 is converted by double XGM; in the second bar the second PC is directly connected to EPON1. Throughput is almost the same in both configurations, with the same average; the main difference is a slight increase of the throughput variance in the XGM configuration, but the amount is negligible and does not affect the performance.

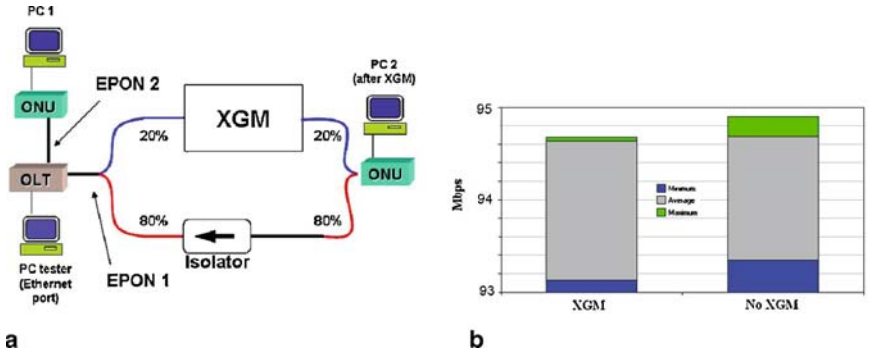

Fig. 4.4 (a) Network setup and (b) throughput with and without cross gain modulation at 1,490 nm for a 10 min test

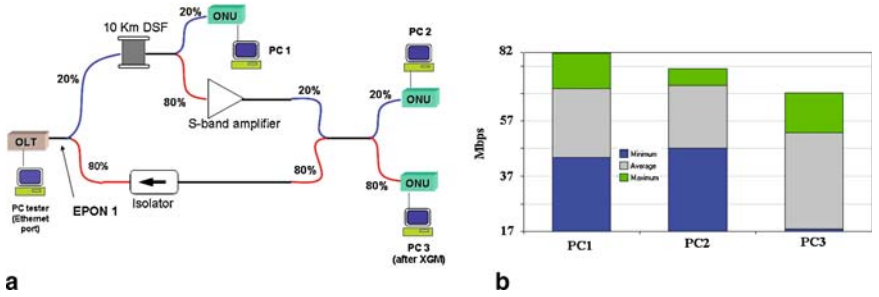

Fig. 4.5 Increase of operated Optical Network Units and network length investigation: (a) Network Setup and (b) throughput

In Fig. 4.5a we show a further step where the increase of operated ONUs and network length are investigated. Figure 4.5b demonstrates that the system performance is still good for high quality transmissions and video applications.

4.1.2 Tolerance to Wavelength Conversion Range

As introduced in section 4.1.1, the possibility to convert an optical carrier in a native Ethernet based passive optical network without performance degradation is real and present. The system is quite robust to optical signal manipulation from S- to C- to S-band. It is interesting to understand that the wavelength coupling range between ONU and OLT with a single XGM.

Table 4.1 shows the throughput at three different wavelengths (1,490, 1,500, 1,520 nm), demonstrating that XGM does not affect the EPON performances.

This result demonstrates that these commercial systems are flexible to wavelength processing/manipulation and respond to XGM induced delay and wavelength conversion with good performances.

4.2 Bidirectional Single Fibre Transmission with Colourless Optical Network Unit

Bidirectional single fibre transmission with colourless ONU constitutes a simple and interesting transmission scheme for applications in the access network domain, mainly because of its cost efficiency in terms of capital expenditure per customer. The use of reflective ONUs constitutes an advanced option towards a unique and simple wavelength-agnostic ONU for WDM PON applications by eliminating the laser source at the ONU and thus avoiding stabilization and complex provisioning at the user premises. As well, by using one single fibre for both transmissions, upstream and downstream, the optical infrastructure size is highly reduced, the connection management of the outside plant is simplified and the micro-bending risks at customer premises are minimized [Sananes05]. This is a basis to fit in a transparent WDM scenario of future fibre-to-the-home networks.

The limitation of bidirectional single wavelength single fibre transmission (BSWSF) systems comes from the presence of Rayleigh scattering and reflection crosstalk. When signals propagate in opposite directions there is a crosstalk between the signal travelling in one direction and the backscattering from the counter propagating signal. This causes coherent and incoherent crosstalk because signals overlap in the detection band.

Some advanced designs have been lately demonstrated which avoid the generation of light at the ONU by using different modulating formats for downlink and uplink transmission: Phase-Shift Keying/Intensity Modulation [Hung03], electro-absorption transceiver for signal remodulation [Schneider02], polarization rotation remodulator [Koonen01] and IM (Intensity Modulation) remodulation using semiconductor optical amplifiers [Takesue02].

Table 4.1 Compared throughputs with and without cross gain modulation

	Average (Mbps)	Minimum (Mbps)	Maximum (Mbps)
All pairs	189,107	93,132	94,899
XGM @ 1,490 nm	94,631	93,132	94,675
No XGM	94,684	93,349	94,899
All pairs	188,874	89,087	94,899
XGM @ 1,500 nm	94,464	89,586	94,675
No XGM	94,568	89,087	94,899
All pairs	189,066	90,192	94,899
XGM @ 1,520 nm	94,590	90,192	94,675
No XGM	94,667	91,954	94,899

4.2.1 Remodulation by Using Reflective Semiconductor Optical Amplifiers

Reflective ONUs based on SOAs constitute an advanced option towards unique and simple wavelength-independent ONUs for WDM PON applications. They are wavelength-agnostic, present the simplest structure for single fibre access, and avoid stabilised laser use [Prat05a], [Langer05].

Full-duplex transmission can be achieved by combining an ordinary photoreceiver and a reflective SOA (RSOA). In such scheme, the downstream signal is partly coupled to the RSOA branch where it is amplified while upstream data is imprinted and the signal is back-reflected towards the OLT. Three different configurations are illustrated in Fig. 4.6.

The first system, depicted in Fig. 4.6a, uses an Amplitude Shift Keying (ASK) modulated downlink signal with a constant offset, which can be ASK remodulated by the RSOA (biased for operating in the saturation region). In the second design (b), Frequency Shift Keying (FSK) modulation is used for downstream transmission. For detection at the ONU, an optical filter converts the FSK signal into IM by selecting the frequency, which corresponds to the logical 'one' of the data stream. The signal for upstream use is coupled to the RSOA where it is orthogonally ASK

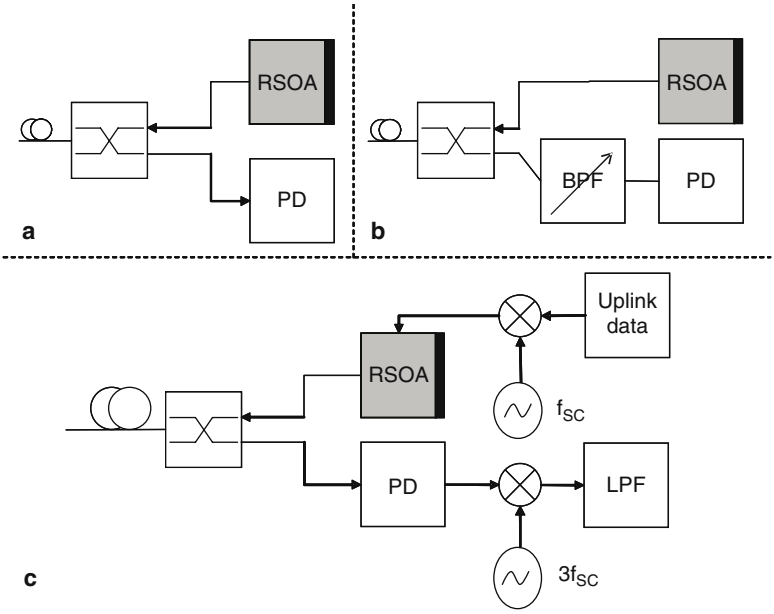

Fig. 4.6 Configuratons of reflective optical network units using different modulation schemes: (a) downlink ASK, uplink ASK; (b) downlink FSK, uplink ASK; (c) subcarrier multiplexed up- and downlink

remodulated. In the third approach (c), the uplink and downlink data are carried on different electrical frequencies. The downlink spectrum is shifted to an electrical frequency at least three times higher than the uplink subcarrier frequency in order to prevent spectral overlapping. By locating the downstream subcarrier outside the RSOA's electrical bandwidth (~1.5 GHz), it acts as an electrical low pass filter. Then the remained power carried into the base band is up-converted and modulated with the uplink data.

4.2.2 *Fabry Perot Injection Locking with High Bandwidth and Low Optical Power for Locking*

The architecture of a typical WDM local access network where a Fabry Perot Injection Locking (FP-IL) is employed at the ONU is depicted in Fig. 4.7 [Chan01].

A wavelength grating router (WGR) is used to route different wavelength channels to different ONUs. Our scheme employs a Fabry Perot Laser Diode (FP-LD) at the ONU (see inset). At the ONU, the downstream wavelength channel is partially tapped off for downstream data reception while the rest of the wavelength power is injected into the FP-LD for injection locking. The injection locking will greatly improve the Side-Mode Suppression Ratio (SMSR) of the FP-LD, which is necessary for DWDM environment. Under the condition that both the ones and zeros power levels of the injected downstream signal are above a certain power threshold, the injection-locked FP-LD will emit the same wavelength as the downstream signal with the original data content largely suppressed. Thus, by direct-modulating the injected-locked FP-LD with the upstream data simultaneously, a potentially low cost upstream data transmitter with improved signal quality can be realised.

4.2.3 *Characterization of Rayleigh Backscattering*

In Fig. 4.8a BSWSF WDM PON architecture is presented. Each user receives a continuous wavelength (CW) from the Central Office (CO). At the ONU it is modulated, amplified and sent back to the CO. The simultaneous transmission of

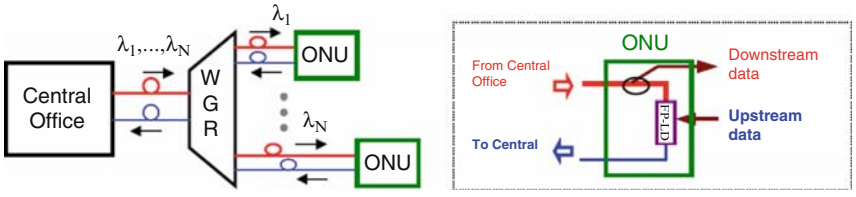

Fig. 4.7 Typical WDM local access network and proposed architecture of the Optical Network Unit

the CW and the upstream modulated signal in the same fibre generates several effects which affect the transmission performance. There are three notable contributions to the total noise in the upstream direction: Rayleigh backscattering, Stimulated Brillouin scattering and reflections from components.

The backscattered light is amplified and remodulated at the ONU together with upstream data. At the CO, the detected signal is formed by the desired uplink data, the noise originated by the upstream Rayleigh backscattering, uplink reflections, and downlink reflections amplified by the ONU.

In the same way, the upstream modulated signal and reflections from components along the link cause Rayleigh backscattered light in the downstream direction, as depicted in Fig. 4.9.

Single reflections can be reduced by using APC (Angled Physical Contact) connectors with low return losses and the effect of Brillouin scattering can be reduced

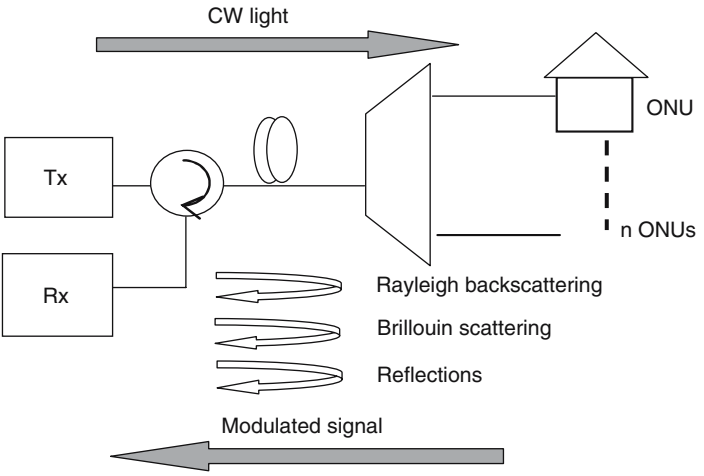

Fig. 4.8 Noise in the upstream direction because of Rayleigh and Brillouin scattering and reflections

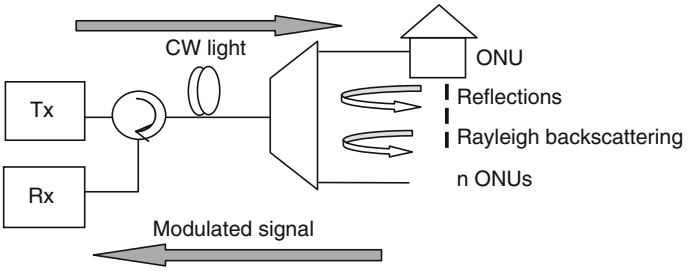

Fig. 4.9 Noise in the downstream direction because of Rayleigh and Brillouin scattering and reflections

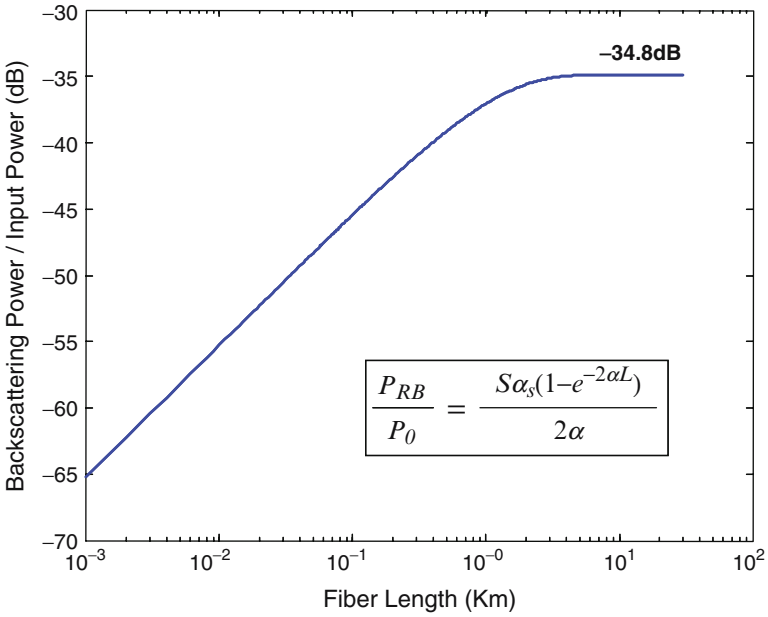

Fig. 4.10 Normalized Rayleigh backscattering intensity versus fibre length; $\lambda = 1{,}550\,\text{nm}$, $S = 10^{-3}$, $\alpha_s = 3.2\ 10^{-2}\ \text{km}^{-1}$, $\alpha = 0.2\,\text{dB/km}$

by using short-coherence length light sources. However, the power of the backscattered signal due to Rayleigh losses depends directly on the power of the CW signal and the gain at the ONU; therefore, it becomes the most degrading effect in a bidirectional system.

The normalized backscattered power along the fibre is depicted in Fig. 4.10. It increases with the length of the fibre and after 20 km it converges to a value of −35 dB, depending on the fibre parameters and the wavelength.

For quantifying the effect of the gain at the ONU on the detected signal at the CO an experimental setup was performed and the Bit Error Ratio (BER) for the uplink was measured. The tested setup is shown in Fig. 4.11. At the CO a DFB laser centred at the wavelength of 1,555 nm was used to inject CW signal into the system. The fibre link between the CO and the ONU was of 20 km. At the subscriber premises, the ONU module was composed by an ElectroAbsorption Modulator (EAM) and two SOAs. The first SOA compensates for the EAM losses at the ONU. After the optical modulation by the EAM, the signal is amplified by the second SOA in order to obtain sufficient power for upstream transmission. To limit the penalties due to reflections, scattering and back-scattering, an optimization of the two gains of the SOAs is necessary. The bit rate for the EAM was 1.25 Gbps. The ASE noise of the SOAs was filtered by the arrayed waveguide grating (AWG). The AWG has a spectral width of 100 GHz and insertion losses of 5 dB. The total link loss by taking into account all the components was 12.5 dB.

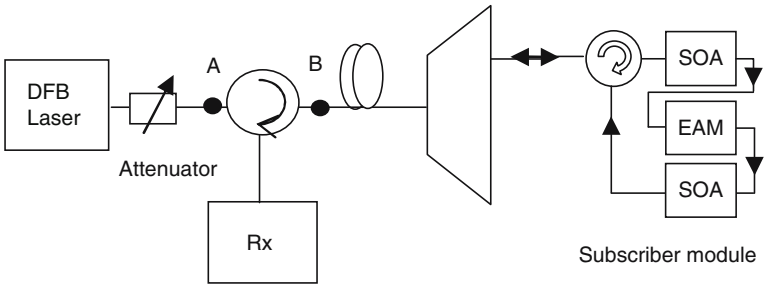

Fig. 4.11 Experimental setup for the quantification of the effect of gain at the optical network unit

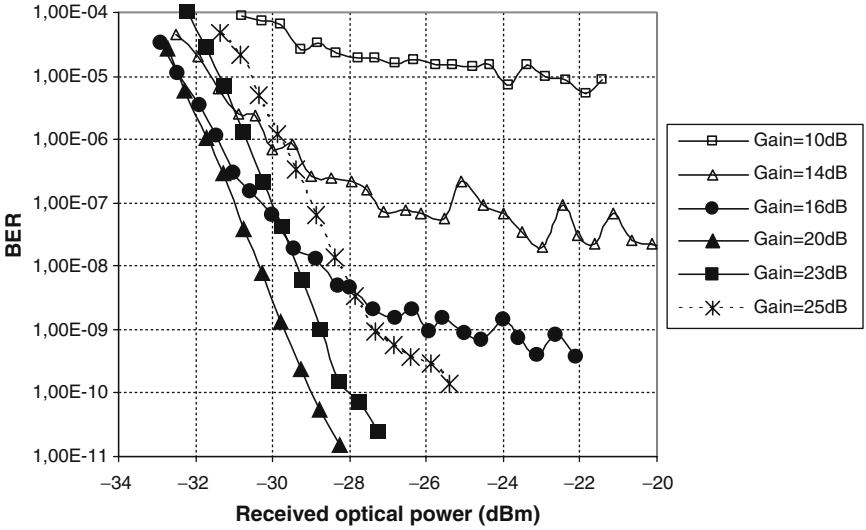

Fig. 4.12 Bit Error Ratio for an input power of −3 dBm in point A

The input power at point A was −3 dBm. The received optical power was measured at point B. Figure 4.12 shows the resulting BER curves. The experimental results showed that by increasing the gain of the ONU up to an optimum value of 20 dB the transmission is improved. For gain values over 20 dB the sensitivity increases. The minimum sensitivity for 20 dB of gain at the ONU was measured −29.8 dBm.

For small values of the gain the backscattered power dominates over the interference caused by a reflection at the ONU side. As the Rayleigh backscattering contribution is constant, the signal to interference ratio increases and then the BER is improved. For higher values of the gain, the power of the interference is over the Rayleigh noise, then the signal to interference ratio is degraded.

4.2.4 Strategies to Mitigate Rayleigh Backscattering

As shown in the previous section, Rayleigh backscattering is an important and unavoidable limiting effect in bidirectional single wavelength systems due to signals propagating in opposite directions along the same fibre cause both coherent and incoherent crosstalk. Since only one light source is used, the coherent and incoherent crosstalks overlap with the signal in the detection band. Coherent crosstalk can be reduced by broadening the spectrum of the optical feeder signal by means of wider spectrum modulation formats. Another technique for crosstalk mitigation is by using electrical Subcarrier Multiplexing (SCM). By multiplexing downstream and upstream signals in the electrical domain, incoherent and coherent crosstalk can be effectively reduced because the spectra of both types of crosstalk lay outside the spectrum of the signal and thus can be removed by electrical filtering after detection. Power budget can also be improved by means of Forward Error Correction (FEC) performance, which is shown to provide efficient coding gain also in Rayleigh crosstalk limited systems [Seimetz04], [Faraj03].

In order to demonstrate modulation and detection properties of SOAs in conjunction with single wavelength single fibre transmission, several ONU configurations were implemented and evaluated. With the aim to improve the ONU robustness to crosstalk due to Rayleigh backscattering, three different transmission techniques were experimentally analyzed. First, ASK data modulation for both uplink and downlink transmission was implemented (ASK-ASK). By adding a constant power offset to the downlink modulated signal it can be ASK remodulated by the RSOA (biased for operating in the saturation region). To avoid the overlapping, a simple time division can be performed with half duplex transmission. In a second scenario, FSK for the downstream data is combined with ASK for the upstream data (FSK-ASK). Finally, SCM in the electrical domain is used for both upstream and downstream channels. Full-duplex transmission in the time domain is performed in the latter two systems. In order to increase the power budget, FEC was also applied to those systems, and the resulting benefits were quantified [Arellano05noc].

4.2.5 ASK-ASK Configuration Using Time Division Multiplexing

The performance results of the first system are shown in Fig. 4.13. The uplink sensitivity (BER = 10^{-9}) was −15 dBm when upstream data was modulated onto a pure optical carrier (CW). As mentioned before, bidirectional systems are limited by crosstalk due to Rayleigh backscattering that can be reduced by broadening the spectrum of the feeder signal. Hence, a way for improve uplink sensitivity is to use PRBS (Pseudo-Random Bit Sequence) downstream signal for remodulation instead of CW light. By using a 1.25 Gbps 2^{23}-1 PRBS signal, a sensitivity of −20 dBm was achieved. Additionally the sensitivity was increased then by another 7 dB by applying FEC in both, the CW and the PRBS case. The RSOA detection capabilities were

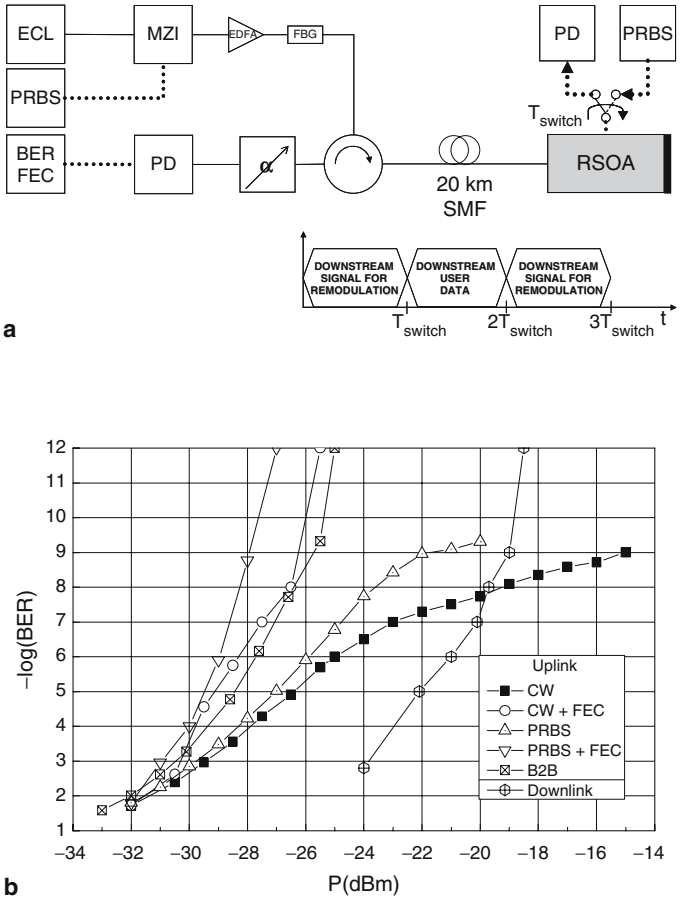

Fig. 4.13 (a) Setup and (b) measurements of Bit Error Ratio for the ASK-ASK scheme

tested by sending the ASK NRZ (Non Return to Zero) modulated signal at 1.25 Gbps from the OLT. At the ONU −19 dBm optical power is needed to achieve a detectable variation of voltage.

4.2.6 FSK-ASK Configuration Using Modulation Format Multiplexing

The second configuration is presented in Fig. 4.14. In the experiments, a four-section GCSR (Grating-assisted Coupler with Sampled Reflector) laser was used to generate the FSK downstream data at 1 Gbps. The optical frequency deviation was 10 GHz and the resultant residual amplitude modulation was 0.4 dB. At the ONU the downstream demodulating section and the upstream remodulation section are separated by an

optical coupler. For FSK detection, a tuneable band-pass filter converted the FSK modulation into intensity modulation by suppressing the transmission frequency corresponding to the zero data. A PIN photo-detector was used to receive the downstream data. As the FSK signal is constant in amplitude, the upstream data can be intensity modulated by the RSOA in the remodulation branch with minor distortion.

The BER curves of the upstream signal modulated over the FSK signal, depicted in Fig. 4.14b, show a sensitivity of −20 dBm, as in the ASK-ASK system. However, the degradation of the BER is more relaxed in this case, which is beneficial at lower optical power levels. Once again, there is an improvement compared to the CW system, since the FSK spectrum is broader than the spectrum of a pure tone. A downlink sensitivity of −23 dBm was achieved for the downlink FSK signal, detected at the ONU.

4.2.7 Subcarrier Multiplexing by Electrical Frequency Multiplexing

The setup for subcarrier multiplexing is depicted in Fig. 4.15. Upstream and downstream signals are multiplexed on different electrical frequencies. A bit rate of 155 Mbps was chosen to be able to accommodate upstream and downstream data in the RSOA electrical bandwidth (1.2 GHz). The subcarrier frequencies were selected with a spacing of 3 × 155 MHz to prevent interference between uplink and downlink signals.

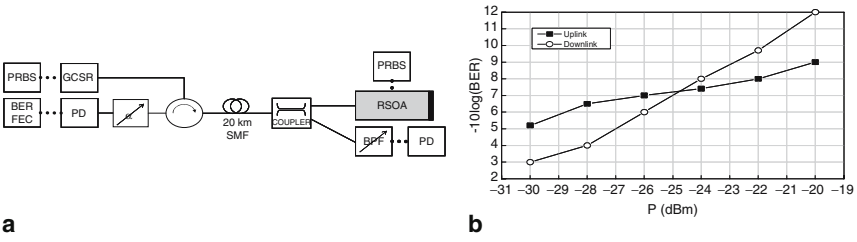

Fig. 4.14 (a) Setup and (b) measurements of the Bit Error Ratio for FSK-ASK operation

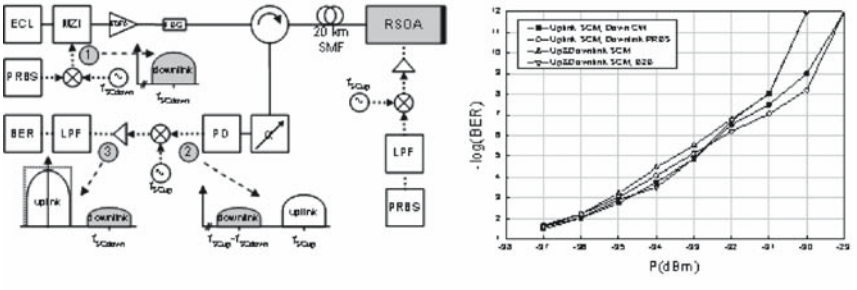

Fig. 4.15 (a) Subcarrier multiplexing test-bed and (b) measurements of the Bit Error Ratio

The uplink SCM oscillator was locked at 852.5 MHz and the uplink information was electrically modulated onto this subcarrier. Three different tests were carried out varying the downlink signal. First, a CW signal without downstream data was sent; second, a base-band ASK-modulated downstream was launched, and finally the downstream was up-converted and transmitted on a subcarrier at 387.5 MHz.

The BER measurements show that there is no significant difference between sensitivities of back-to-back and 20 km Single Mode Fibre (SMF) transmission when upstream data is multiplexed in the electrical domain using SCM. The sensitivity was measured −30 dBm. This result, which is consistent for each of the three downlink experiments, reveals that the Rayleigh effect is greatly reduced whenever upstream and downstream data are transmitted on different electrical frequency bands. A graphical explanation can be taken by regarding the evolution of the spectrum at points 1–3 in Fig. 4.15. As the backscattered signal from the downlink is located in a different frequency range than the uplink signal, the related crosstalk is hardly of relevance.

4.2.8 Rayleigh Scattering Reduction by Means of Optical Frequency Dithering

This method consist in applying a pilot signal to a tuneable laser, adequately adjusting the amplitude, frequency and waveform of the pilot for reducing the crosstalk caused by Rayleigh scattering in bidirectional centralized light systems [Lazaro07B].

In the literature, the effect of the Rayleigh Backscattering (RB) has been precisely determined for Lorentzian-shape optical spectrum. Since RB variance reduction is directly related to the optical spectral components that are heterodyned out of the electrical bandwidth, an effective way of obtaining the spectral broadening may consist on sweeping modulation of the optical frequency by using a tuneable laser, thus decreasing the B_e/B_o ratio (B_e is the receiver electrical bandwidth and B_o is the optical signal bandwidth). Figure 4.16 shows the heterodyned Lorentzian spectrum of a GCSR tuneable laser (NYW30). The measured laser linewidth of the spectrum reveals that the FWHM (Full-Wave Half-Maximum) bandwidth is about

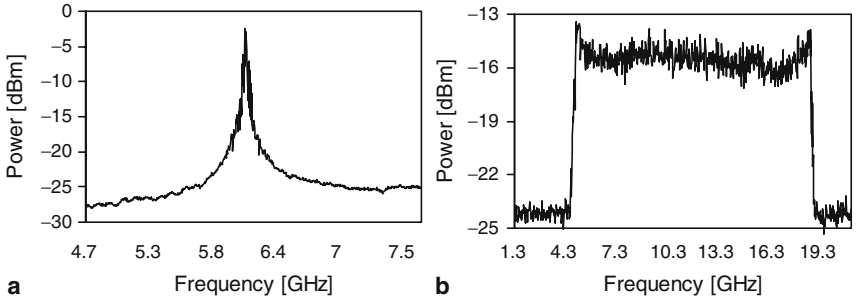

Fig. 4.16 (a) Lorentzian laser spectrum; (b) frequency modulation spectrum with triangular modulation

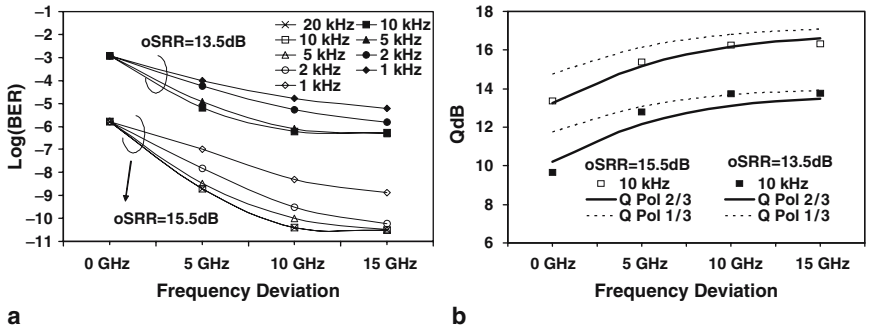

Fig. 4.17 (a) Bit Error Ratio as a function of the deviation of frequency modulation for different modulating frequencies with triangular modulating waveform; (b) corresponding QdB parameter values for the 10 kHz modulation frequency series and comparison with estimations from (4.1) and (4.2)

25 MHz. Figure 4.16b shows the resultant broadened spectrum after introducing a triangular signal of 10 kHz and 0.55 mA of amplitude to the reflector tuning section, thus yielding a total of 15 GHz frequency deviation.

A significant improvement in the BER when applying the pilot tone with a triangular waveform is observed (between 3 and 4 orders of magnitude). The improvement, as it can be seen in Fig. 4.17a stabilises for frequency deviations above 10 GHz and for frequency modulations above 10 kHz. On the other hand, it is strongly reduced for frequencies below 5 GHz (deviation) and 1 kHz (modulation).

An analytical expression for the Q-parameter of the signal in systems affected by RB can be given. Starting with expressions of RB statistics from [Das02], [Gysel00] and following the analysis shown in [Lazaro07a], it can be shown that the Q-parameter of the signal affected by RB, Q_{RB}, can be described, in case of non-applied optical frequency dithering by:

$$Q_{RB} = 2Q_{REF} \Big/ \left(1 + \sqrt{1 + 4K_{POL} oSRR^{-1} Q_{REF}^2 \left(2/\Pi\right) \arctan\left(B_e/B_o\right)}\right) \qquad (4.1)$$

where Q_{ref} represents a reference Q-parameter of the signal in absence of RB, K_{POL} is the fraction of the total P_{RB} in the same state of polarization (SOP) as the signal and oSRR is the optical Signal-to-Rayleigh Backscattering Ratio.

In case of applying an optical frequency dithering, the Q_{RB} can be calculated by:

$$Q_{RB} = 2Q_{REF} \Big/ \left(1 + \sqrt{1 + 4K_{POL} oSRR^{-1} Q_{REF}^2 2\left(B_e/B_o\right)}\right) \qquad (4.2)$$

Figure 4.17b shows the results obtained from analytical expressions (4.1) and (4.2) in comparison with the results for frequency modulations of 10 kHz with triangular waveform, shown in Fig. 4.17a by their Q_{dB} values. For the null frequency deviation point (4.1) is used with B_0 = 25 MHz. It is adequate as, in our setup, the upstream

signal is ASK modulated by the Mach-Zehnder Modulator (MZM) of the ONU and such modulation does not modify the incoming Lorentzian profile, but only at power levels −15 dB under the maximum [Zacharopoulos05]. For the rest of the points, Eq. (4.2) with B_0 = Frequency-Deviation has been used. Theoretical results have been calculated for the worse (solid line in Fig. 4.17b, K_{POL} = 2/3) and the best case (dashed line, K_{POL} = 1/3) [VanDeventer93].

The expressions (4.1) and (4.2) provide then a straightforward way to calculate the reduction of the RB impairment provide by the frequency dithering of the optical signal source. In case of for large frequency deviations, an expression for the penalty can be given as $Q_{penalty} \approx 20log[1-K_{POL}oSRR^{-1}Q^2{}_{REF}2(B_e/B_o)]$.

Summarizing, the introduction of a pilot signal of several tens of kilohertz into the laser source tuning is a simple approach to reduce RB in centralized-light bidirectional single fibre access systems.

4.3 Spectral Slicing

In WDM PON systems, it is advantageous to deploy wavelength-agnostic ('colourless') ONUs, in order to avoid wavelength-specific equipment at each end user. This allows to have a universal ONU at each user, and thus reduces costs by economy-of-scale and less stock diversity. Spectral slicing is an attractive approach for such a colourless ONU. The principle is illustrated in Fig. 4.18a.

A broadband light source (e.g. a Light Emitting Diode, LED) is deployed in the ONU, of which the FWHM spectral width is at least equal to the wavelength band of the WDM PON system. The wavelength router located in the PON splitting point performs bandpass filtering in each fibre link to an ONU, and takes a specific slice for each ONU out of the LED spectrum. Thus, no accurate wavelength control of the ONU is needed, which eases the ONU design. On the other hand, the net upstream available power is limited by the slice width.

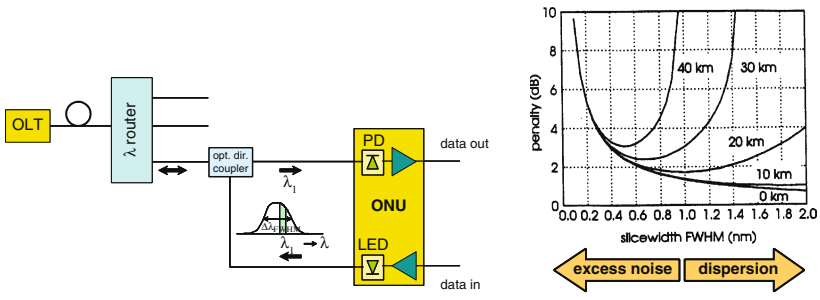

Fig. 4.18 (a) Spectral slicing; (b) dependence of the Optical Line Terminal receiver penalty on spectral slice width for various fibre lengths

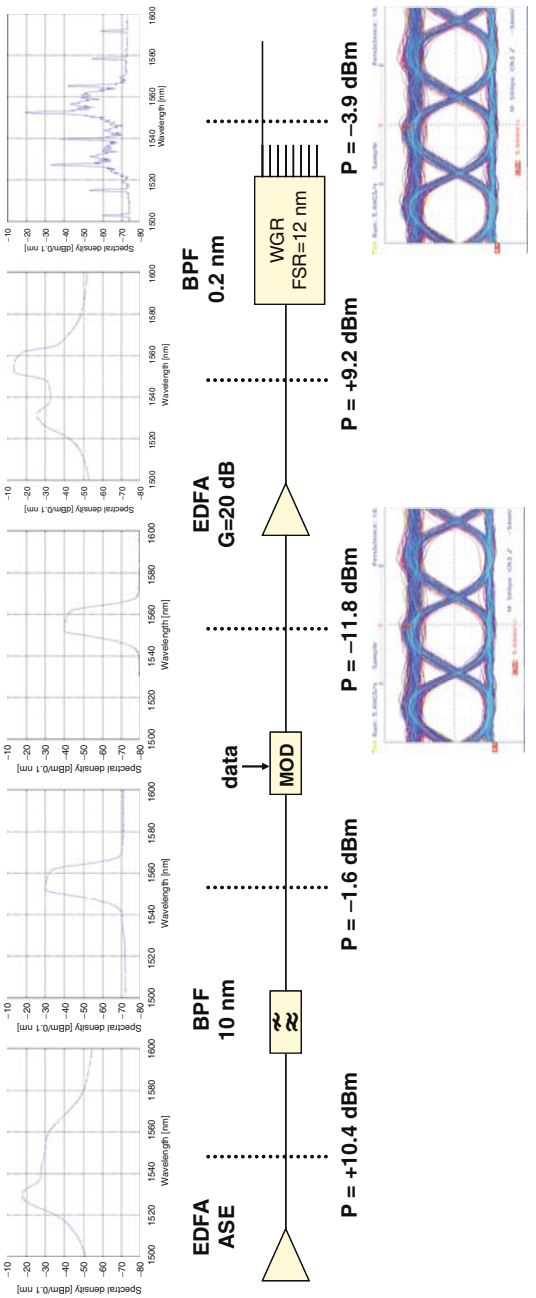

Fig. 4.19 Spectral slicing experiment

To increase the upstream power, a larger slice width would be preferred, but that will lead to a higher fibre chromatic dispersion penalty, depending on the length of the fibre link up to the OLT. A smaller slice width will not only reduce the upstream power, but will also increase the excess noise inherent to spectral distribution instabilities of the LED. Hence an optimum slice width exists, which depends on the fibre length. For a 1.244 Gbps system and a LED spectrum centred at 1,550 nm, Fig. 4.18b shows how the OLT receiver penalty depends on the slice width for various fibre link lengths, and thus how the optimum slice width varies with fibre length [Pendock96].

To illustrate the impact of the source excess noise by too narrow slice width, Fig. 4.19 shows how the data eye pattern deteriorates when the slice width is decreased in case of the broadband light source being an EDFA generating ASE.

4.4 Alternative Modulation Formats to NRZ ASK

The standard modulation format in current Fibre-to-the-Home (FTTH) is the conventional intensity-modulation direct-detection (IM-DD), with direct modulation TX laser to save the external optical modulation cost and loss. However, there are new scenarios where this may change. For the single fibre with reflective ONU architecture, as described in the previous section, the modulation format is relevant to overcome the optical interference.

On the other hand, in future extended-range access, distances may reach much farther than the standard 20 km limit, since the aimed extended PON not only supports very high splitting ratio but also higher bit rates and long distances in order to cover a metropolitan area. In such a case, the new advanced modulation formats that allow distances up to 100 km with simple optics, direct laser modulation, electronic signal processing and compact spectrum can be applied effectively here, probably in their simplest variant options, as cost is the prime requirement; some are being developed for the core network. For example, optical dispersion compensators are to be avoided thus dispersion-tolerant formats and electronic digital equalization can be developed in this area, taking advantage of the new integrated fast digital signal processors. At the TX the laser chirp is to be minimized, thus integrated-modulator lasers (IML) with EAM can be adequately used. The other commented option is direct FSK modulation, although requiring an optical FM discriminator [Mahgerefteh05] [Prat05dfsk].

A further improvement to FSK that has been developed is Duobinary-FSK, where the duobinary signalling concept is applied onto direct frequency modulation of a semiconductor laser [Prat05dfsk]. The main goal is the achievement of low cost high bit rate transmission with reduced modulation bandwidth requirement of the laser diode, and the avoidance of the optical modulator losses and its high power driver. The simulation and experimental work demonstrate a remarkable laser modulation bandwidth requirement reduction of about 50%. Furthermore, the system exhibits a high tolerance against fibre non-linear effects, up to 20 dBm, and

phase noise up to a linewidth of 170 MHz at future 10 Gbps access, at an optimum modulation index of m = 2 × 0.5 (Minimum Shift Keying, MSK).

In IM-DD, a non-linear memory-less electronic function after the photo-detector has been proposed that makes the transmission channel more linear, enhancing the performance of the recent fast linear electronic equalization (EE) and reducing the intermodulation harmonics in Radio-over-Fibre (RoF) systems (Composite Second Order CSO, Composite Triple Beat CTB). Results showed a clear improvement in terms of chromatic dispersion tolerance, by simply applying a mathematical square root operator after the optoelectronic conversion at the receiver: with the SQRT, the distance range can be extended in between +60% and +100%, depending on the EE complexity [Prat05sq]. The same module has been successfully applied over Radio-over-Fibre systems for distortion reduction.

In a longer term approach, a notorious technological advance that may assure the upgradeable evolutionary path could consist in the so called Ultra-Dense Wavelength Division Multiplexed (UDWDM) networks, making use of the same transparent extended PON infrastructure deployed. In UDWDM, users could tune their ONU to any one of the hundreds/thousands of wavelength channels, spaced at very few gigahertz. A novel Phase Shift Keying (PSK) homodyne receiver technique is proposed based on I&Q electronic differential processing, featuring high tolerance to phase noise and feasible implementation with commercial lasers [Prat05iq]. The new DPSK architecture remarkably increases, in about two orders of magnitude, the phase noise tolerance of conventional homodyne receivers, up to a linewidth of 1% R_b, and avoids the use of an optical Phase-Locked Loop (oPLL). This architecture is specially indicated for standard-linewidth slow tuning semiconductor lasers and even for low bit rate access systems. Thus, it constitutes an enabling technique towards UDWDM networks, featuring few gigahertz spacing wavelengths with electrical channel filtering, simple tuning and low sensitivity.

4.5 Bidirectional Very High Rate DSL Transmission Over PON

This section describes some of the experimental work conducted at the University of Essex, UK, studying the transmission of multiplexed analogue xDSL signals over an optical carrier. The work has been funded under the EU Muse integrated project [Vetter05] and for further details many of the results briefly discussed herein have been published elsewhere (for example, [Lepley05], [Thakur05], [Lepley04]).

One considerable expense in deploying DSL (digital subscriber line) over an Fibre-to-the-Curb (FTTC) architecture is the requirement for the installation of a remote digital subscriber loop access multiplexer (DSLAM), deployed in the ONU. The heavy power requirement and increased footprint of such systems places a significant burden on both the capital expenditure and operating expenditure (CAPEX and OPEX respectively) of this architecture, and alternatives are sought. In this work, we present a scheme to provide fibre optic extended DSL signals over an FTTC architecture with inexpensive low power (<600 mW) ONU interfacing equipment

whilst retaining the DSLAMs at the CO. Furthermore, provision for multi-dwellings or multiple CPEs is afforded through the use of subcarrier multiplexing in the ONU/OLT interfacing equipment. A noteworthy advantage of this system is that it provides a readily deployable upgrade path for fibre penetration into legacy copper-based access networks. This could form part of a staged upgrade solution that, with sufficient uptake of triple play services, could culminate in an FTTH network.

We study two ONU hardware architectures; the first uses a conventional optoelectronic interface comprising a laser and photodiode. This could, for example, consist of a bidirectional (BiDi) optical transceiver or of a photodiode and laser pair. A particularly suitable choice of laser for this application would be the Vertical Cavity Surface Emitting Laser (VCSEL) as it is inherently inexpensive and suited to integrated circuit design. In a further implementation of the ONU hardware, we describe an optical interface consisting of a photodiode and a RSOA. The RSOA consists of a conventional SOA in combination with a rear facet mirror such that the amplified lightwave is retro-reflected. This characteristic provides an increased gain from the device due to the double pass of the light through the gain region; an additional characteristic is their ability to modulate the incoming signal, removing the need for a local light source. Although the present cost of RSOAs would make this particular solution economically unviable at present, there is now some research interest in vertical cavity semiconductor optical amplifiers (VCSOAs), with demonstrated optical gains of >10 dB. Such devices, being closely related to VCSELs, offer the potentially low manufacture and construction costs required for consumer products. Moreover, their "uncoloured" nature may lead to significant cost savings of the ONU devices due to the economies of scale and logistical benefits of using a generic system design.

Figure 4.20 presents the link structure used to carry multiple DSL signals over a FTTC network. The network contains some key feature, amongst which are the compatibility with PON architectures and retention of the Central Office DSLAM equipment. An ONU multiplexes each of the DSL signals from the CPE, with a maximum of 24 VDSL (Very high data rate Digital Subscriber Line) bandwidth signals expected to be contained within a 1 GHz modulation bandwidth optical carrier using the current implementation. Future designs may encompass single/vestigial sideband techniques to improve the spectral efficiency of the subcarrier signals.

A set of hardware has been developed, based around the architecture of Fig. 4.20. Figure 4.21 shows a schematic of the experimental setup. The system comprises a DSL modem at the CPE carrying 100BASE-T fast Ethernet traffic over a VDSL band 998 compliant channel. This is connected to the ONU equipment by 24 AWG CAT-3 UTP (unshielded twisted-pair) cable with a loss of ~0.1 dB/m at 10 MHz. Clearly final drop cables can vary in quality quite substantially and may suffer from crosstalk issues as well as impairments from the electrical characteristics of, for example, bridged-taps and splices. The bit-loading characteristics of the modem would attempt to optimise the performance of the data link even over such poor quality links, however this may ultimately lead to a slight variation in the data carrying capabilities of certain legacy copper cables.

The UTP from each CPE terminates in the hardware represented by the ONU in Fig. 4.21. The line initially terminates into an electronic directional coupler to split

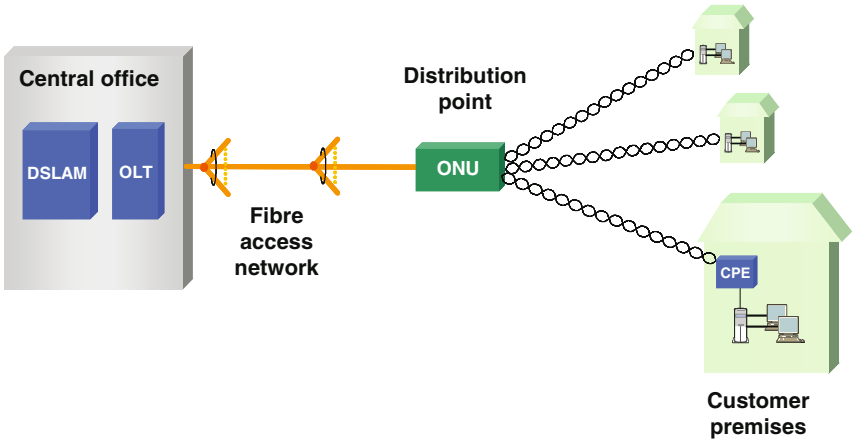

Fig. 4.20 Network architecture used for DSL over optics solution

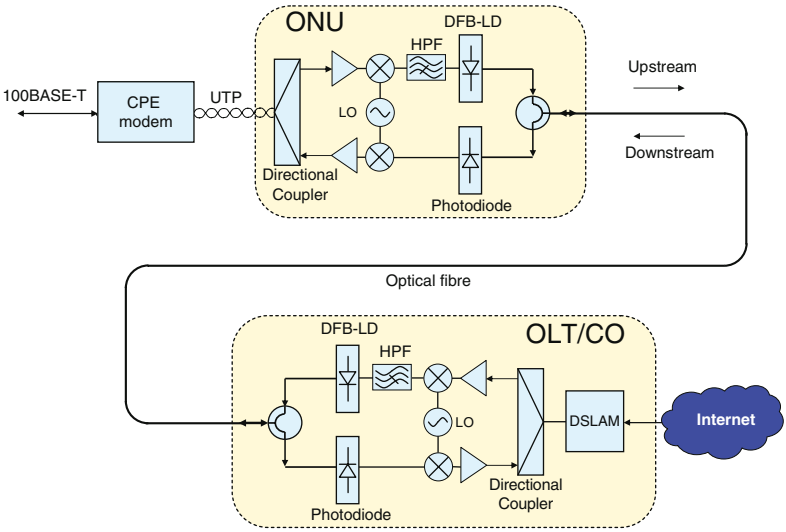

Fig. 4.21 Very high rate DSL over Fibre-to-the-Curb experimental setup

the upstream and downstream signals. The design of the directional coupler consists of a lossless differential balanced op-amp pair with a measured isolation of 23 dB in the forward direction and >80 dB in the return direction. The forward direction is defined here as being from the optical receiver towards the modem or DSLAM termination (i.e. the direction of the arrows in Fig. 4.21) and the converse is true for the reverse direction. The directional coupler has been further designed to be frequency independent, thereby allowing for a band-plan-agnostic ONU solution capable of carrying both QAM (Quadrature Amplitude Modulation) and DMT (Discrete

MultiTone) based signals. This design characteristic of both the OLT and ONU equipment makes the scheme capable of carrying true interoperable universal-DSL signals. Other designs for the directional coupler were considered, amongst which are the transformer based hybrids and directional couplers. However, these suffer from limited up/downstream isolation and significantly higher losses.

The differential output of the directional coupler is converted to a common-mode signal before being upconverted to a channel within the SCM spectrum. A passive high-pass filter is used after the mixer to remove the residual baseband signal that results from imperfect conversion. In the forward path, the upconverted signal is combined with the other SCM channels before being used to directly modulate a semiconductor laser, although the combined circuits are not shown in Fig. 4.21 to avoid duplicity and because multiple channels have not been transmitted in this experiment. Frequency up-conversion of the DSL signals enables multiple signals to be combined within the ~1 GHz modulation bandwidth of the optical components. In the current scheme, the VDSL signals have a base band spectral width of 12 MHz (24 MHz including both sidebands). With the 998-138-1200 spectral band plan (as defined in the ETSI (European Telecommunications Standards Institute) specification [ETSI270]) this offers a maximum 67 Mbps upstream and 40 Mbps downstream data transmission rate. Given the spectral width of the up-converted signal, a 1 GHz modulation spectrum in the optical carrier would permit 40 VDSL channels, however with the inclusion of 16 MHz guard-bands the channel count would be reduced to ~25. In the return path, the output of the circulator is connected to a photodiode before being passively split, down-converted and re-applied as the return signal to the directional coupler. The output of the laser is connected by a circulator to the fibre link which consists of an unamplified section of non-zero dispersion shifted fibre (NZDSF) fibre with various lengths. The fibre carries the signal to the OLT terminal equipment which comprises an identical circuit to the ONU, the output of which connects directly to the CO modem (or DSLAM). For experimental purposes both OLT and ONU transmitters operate within the 1,550 nm band.

Results obtained demonstrate two key experimental observations. Firstly, the transmission performance of the each VDSL signal over a range of subcarrier multiplexed channels can be assessed. This was performed across the approximate frequency range 50–1,000 MHz, principally governed by the mixer bandwidth. Secondly, performance across increasing optical distance can be observed. Figure 4.22 shows baseline performance of the modem transmission rate through the ONU/OLT equipment for a range of subcarrier frequencies. The results indicate a mean downstream rate of 46.4 Mbps and an upstream rate of 24.1 Mbps, these compare to the 67 Mbps and 40 Mbps respectively available to the fast-998 band plan used, corresponding to transmission efficiencies of 69% and 60% respectively. The decreased efficiency results almost exclusively from the up- and down-conversion processes, namely the conversion loss of the mixers. It is expected that this efficiency could be improved with better linearization in the mixers. For comparison, the worst case measurements from Fig. 4.22 were 40.7 and 20.4 Mbps for upstream and downstream respectively (corresponding to 61% and 51% transmission efficiencies).

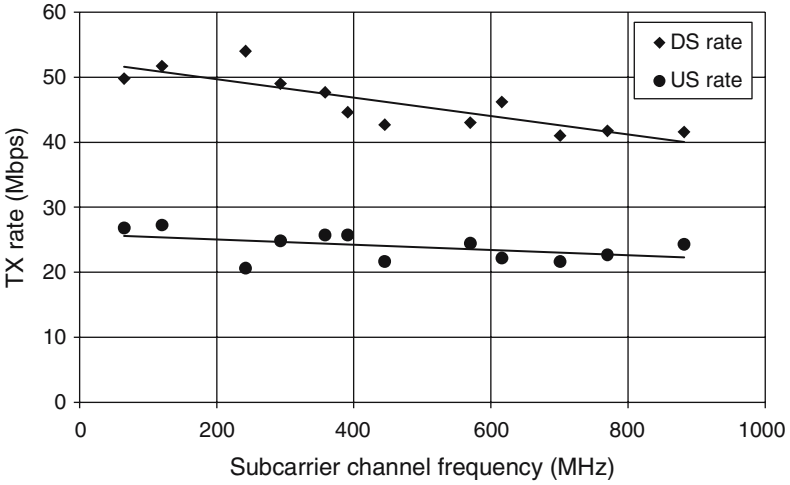

Fig. 4.22 Baseline data rate versus subcarrier frequency though the optical line terminal + optical network unit interface

The variability of the results was partly due to phase mismatching between the local oscillator and the received signal in the down-conversion mixers, which could be removed by incorporating a phase-locked loop into the circuit design.

As a measure of the unconverted efficiency, transmission of base band signals through the same circuit (i.e. bypassing the mixers) produced data transmission efficiencies of 91% and 97% for the down- and upstream signals respectively. This resulted in transmission rates of 96 and 48.5 Mbps over a 105/50 extended-998 band plan.

To measure transmission performance over the fibre optic extended link, the setup of Fig. 4.21 was used with increasing lengths of NZDSF fibre and again performance was measured as an average across the full subcarrier spectrum. The results for baseline optical (i.e. a patchlead), 20 and 45 km of the fibre show a gradual decrease in the data rate with distance reducing the mean downstream rates to 37 and 28 Mbps for 20 and 45 km respectively whilst the upstream rates are reduced 24 and 12 Mbps for the same respective distances. In keeping with the expected access topologies no optical amplification was used. The results therefore follow a predictable degradation due to the increased losses and their consequent reduced signal to noise ratio, as received by the modems.

Chromatic dispersion is not thought to be an issue with this scheme due to the small (12 MHz single sideband) bandwidth of the data signals. A further test with 25 km G.652 SMF (with its' higher dispersion) incurred a similar penalty to the 20 km section of NZDSF and a further experiment, replacing the fibre link with a Dispersion Compensation Fibre (DCF) module (with a dispersion of −1,300 ps/nm at ~1,550 nm, designed to compensate for ~75 km of G.652 fibre) of similar loss to the 20 km NZDSF, again incurred similar transmission results to the 20 km NZDSF measurement.

For the second part of this work, the design of the ONU equipment has been altered to include the RSOA device (as shown in Fig. 4.23). The OLT equipment remains the same as that shown in Fig. 4.21.

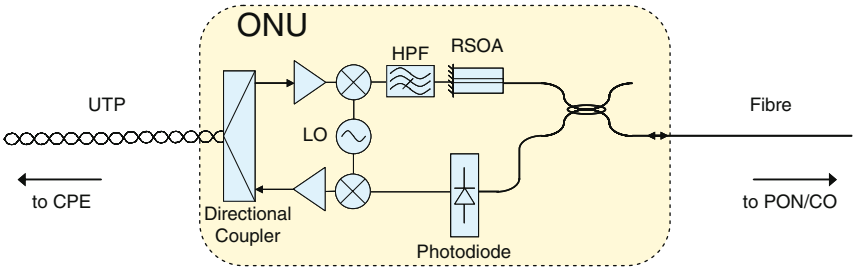

Fig. 4.23 Reflective Semiconductor Optical Amplifier based Optical Network Unit

In this ONU configuration the RSOA is used as a carrierless transmitter, in that it amplifies and modulates the reflected light beam rather than generating a new light beam. This extends the functionality of the RSOA-based ONU to wavelength assignment or routing architectures, and the colourless nature of the ONU designs may lead to positive reductions in the cost of the ONUs as the design becomes more generic.

As the nature of the DSL signal is such that downstream and upstream data are frequency division multiplexed (FDM), the residual downstream signal that is amplified and reflected is effectively filtered by the DSLAM. A separate photodiode is used for detection of the downstream carrier signal. The up and downstream paths are power split using a 3 dB coupler, with care taken to ensure that Fresnel reflections (which may lead to optical feedback in RSOA) are minimised. As with the previous setup, the DSL signal used is the 998 compliant VDSL standard with a 12 MHz spectral bandwidth and a maximum 67 Mbps downstream and 40 Mbps upstream data rate.

Both base band and SCM-based transmission tests were conducted to validate the operation of the RSOA-ONU architecture. The device had a transparency current of 50 mA and was biased at 80 mA; the upstream data modulated on it at a 40 mA peak-to-peak current. Under these conditions, the RSOA provided a gain of ~8 dB, which is sufficient to ensure transparency of the ONU with ~1.5 dB of additional gain. The modulation bandwidth of the RSOA was ~1.5 GHz, although the end-to-end bandwidth of the optical system was restricted to ~1 GHz by the OLT components.

Firstly, the ONU was operated in the subcarrier multiplexing mode using an up-conversion frequency of 260 MHz and the 998 67/40 band plan. With an unamplified 20 km section of NZSDF fibre separating the ONU and OLT, the data rates achieved were 38 Mbps downstream and 24 Mbps upstream, giving data transmission efficiencies of 57% and 60% respectively. These measurements show almost identical performance to those of the previous transmitter design, suggesting that the RSOA would be an equally capable transmitter. With the mixer circuit bypassed to transmit in base band mode, the data transmission rates were 48 Mbps downstream and 25 Mbps upstream, demonstrating data transmission efficiencies of 72% and 63% respectively.

4.5.1 *Heterodyning Systems*

Carrying multi-gigahertz analogue signals over fibre by intensity modulation/direct detection techniques (IM-DD) requires very high frequency optical analogue transmitters and receivers, including careful fibre dispersion compensation techniques. An attractive alternative avoiding the transport of multi-gigahertz intensity-modulated signals through the fibre is to apply heterodyning of two optical signals of which the difference in optical frequency (wavelength) corresponds to the microwave frequency. When one of these signals is intensity-modulated with the baseband data to be transported, and the other one is unmodulated, by optical heterodyning at the photodiode in the receiver the electrical microwave difference frequency signal is generated, amplitude-modulated with the data signal. This modulated microwave signal can via a simple amplifier be radiated by an antenna; thus a very simple low cost radio access point can be realised, while the complicated signal processing is consolidated at the head-end station.

This approach, however, requires two light sources with narrow spectral linewidth and carefully stabilised difference in optical emission frequency. An alternative approach requiring only a single optical source per microwave channel is shown in Fig. 4.24 [Griffin99]. The optical intensity-modulated signal from a laser diode is subsequently intensity-modulated by an external MZM which is biased at its inflexion point of the modulation characteristic and driven by a sinusoidal signal at half the microwave frequency. At the MZM's output port a two-tone optical signal emerges, with a tone spacing equal to the microwave frequency. After heterodyning in a photodiode, the desired amplitude-modulated microwave signal is generated. The transmitter may also use multiple laser diodes, as depicted in Fig. 4.24, and thus a multi-wavelength radio-over-fibre system can be realised with a (tuneable) WDM filter to select the desired wavelength radio channel at the antenna site. The system is tolerant to fibre dispersion, and also the laser linewidth is not critical as laser phase noise is largely eliminated in the two-tone detection process.

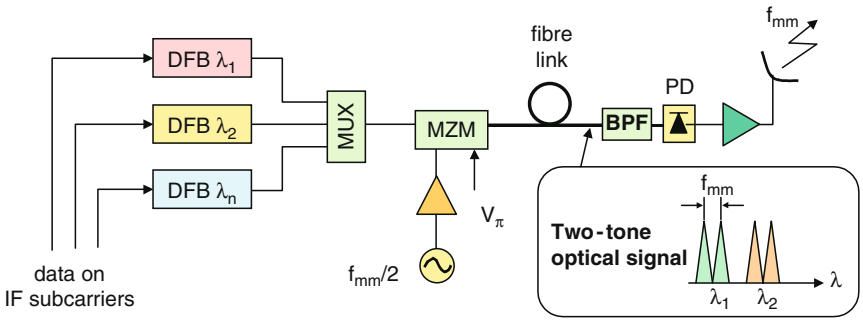

Fig. 4.24 Generating microwave signals by heterodyning

4.5.2 *Optical Frequency Multiplying Systems*

An alternative approach to generate microwave signals by means of a different kind of remote optical processing, named optical frequency multiplying, is shown in Fig. 4.25 [Koonen02], [Koonen03]. At the head-end station the wavelength λ_0 of a tuneable laser diode is swept periodically over a certain range $\Delta\lambda_{sw}$, with a sweep frequency f_{sw} Alternatively, the wavelength-swept signal can be generated with a continuous-wave operating laser diode followed by an external phase modulator that is driven with the integral of the electrical sweep waveform. The intensity of the wavelength-swept signal is on/off modulated with low frequency chirp by the downstream data in a symmetrically driven MZM. After travelling through the fibre network, the signal transverses at the receiver an optical filter with a periodic bandpass characteristic. When the wavelength of the signal is swept back and forth over N filter transmission peaks, the light intensity impinging on the photodiode fluctuates at a frequency $2N{\cdot}f_{sw}$ Thus the sweep frequency is multiplied, and a microwave signal with carrier frequency $f_{mm} = 2N{\cdot}f_{sw}$ plus higher harmonics is obtained. The intensity-modulated data is not affected by this multiplication process, and is maintained as the envelope of the microwave signal. The microwave signal is subsequently transversing an electrical bandpass filter (BPF) to reject the unwanted harmonics. Simulations have shown that the microwave signal is very pure, showing an extremely low phase noise; the inherent cancellation of the laser's optical phase noise makes that the spectral linewidth of the microwave signal is much smaller than that of the laser diode. Experiments have shown a microwave linewidth less than 50 Hz,

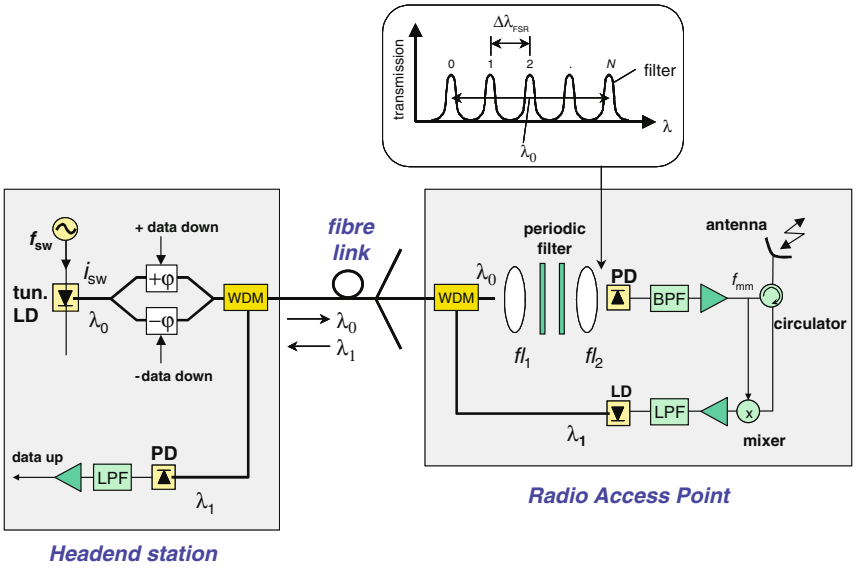

Fig. 4.25 Generating microwave signals by optical frequency multiplying

whereas the laser linewidth exceeded 1 MHz [Ngoma03]. The periodic optical bandpass filter can be advantageously implemented by a Fabry-perot filter with a free spectral range $\Delta\lambda_{FSR}$ which is N times as small as the wavelength sweep range $\Delta\lambda_{sw}$. Benefiting from the very low microwave carrier phase noise, the microwave signal can also carry advanced data modulation schemes; e.g. 16-level Quadrature Amplitude Modulated (16-QAM) signals may be modulated on a subcarrier first, and then drive the Mach-Zehnder Modulator. The main advantage of this optical frequency multiplying method is that only relatively moderate sweep frequency signals are needed at the head-end site (e.g. an f_{sw} up to 1 GHz), which can be generated with low phase noise, while at the antenna site low phase noise microwave signals with carrier frequencies in the tens of gigahertz region are generated. The system does not rely on heterodyning, and thus may also operate on multimode fibre networks (such as polymer optical fibre, which is easy to install inside buildings).

Assuming a linear behaviour of the fibre, it can be shown that the periodic optical filter may also be positioned at the head-end site, yielding the same optical frequency multiplication at the receiving end. Thus, the complexity of the antenna site is reduced further, and the characteristics of the filter can be readily tuned to the frequency sweep of the laser diode [Koonen04].

The system can also transport upstream data from the antenna station to the head-end. By using a simple tuneable local oscillator and a mixer, the microwave carrier generated at the antenna station by the optical frequency multiplying process can be down-shifted, and be used for down-converting the upstream microwave signal from the mobile terminal to a tuneable intermediate frequency. This down-converted signal can subsequently be transmitted upstream on a separate wavelength by an IF optical transmitter.

4.5.3 Coherent Systems

Nowadays, optical fibre communications are, in a certain sense, as primitive as radio communications when crystal (Galena) radio receivers were used. The reason is that there is no need to recover phase information of the optical carrier. Among all, coherent optical transmission systems were investigated at the late 1980s, but abandoned due to its electronics limitations and the irruption of the EDFA at the beginning of the 1990s. Almost 20 years after, technology is more advanced, and allows a full development of coherent systems.

Coherent systems present many advantages with respect to the conventional direct detection systems because of its excellent wavelength selectivity and low sensitivity [Kazovsky06]. First, when using a coherent receiver in a WDM environment, channel selection is done after photo-detection, i.e. by an electrical filter (instead of an optical filter). Thus, selectivity is defined by this filter performance. Regarding sensitivity, coherent reception allows to use PSK and other advanced modulation formats. That is the reason why they can improve sensitivity about 10 dB up to 25 dB, when compared to a IM-DD system [Senior85].

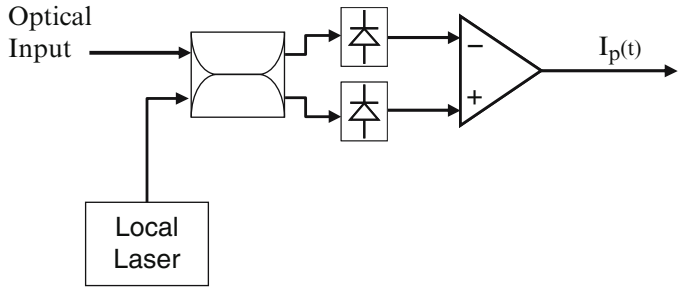

Fig. 4.26 Coherent receiver scheme

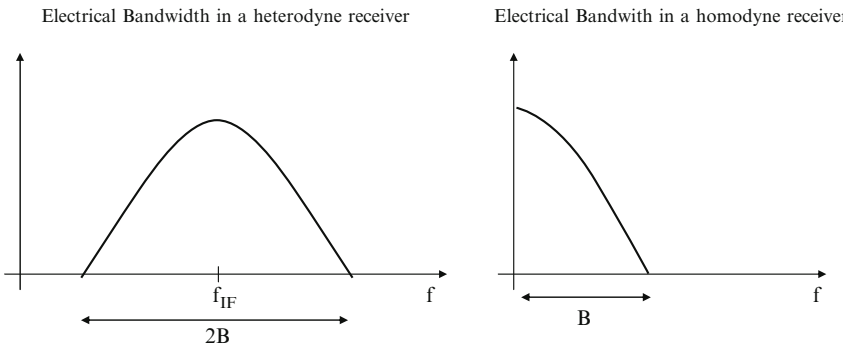

Fig. 4.27 Comparison between homodyne and heterodyne spectrums after photodetection

The main difference between DD and coherent systems is that the received signal is mixed with a local laser output in a coupler. Afterwards, the resulting combination is then photo-detected. This is shown in Fig. 4.26. The current after photo-detection $I_p(t)$ has all information carried by the received optical field.

Depending on the use of an intermediate frequency stage, coherent systems can be homodyne or heterodyne.

In a heterodyne system, the incoming signal is downconverted into an intermediate frequency (usually higher than the bit rate). Afterwards, in a second stage, the signal is mixed with an electrical oscillator for downconverting it into a baseband signal. Since signals are electrically synchronized inside intermediate frequency module, it is an interesting implementation of a synchronous receiver. It avoids the need of very narrow lasers. However, the problems are:

- This intermediate frequency is very high, limiting the functionality of electronics.
- The electrical spectrum is doubled, thus introducing a 3 dB penalty, as shown in Fig. 4.27. An additional filter should be placed in order to avoid image frequency in a multi-channel environment.

A further simplification, at least at a first glance, is the use of homodyne systems. In such systems intermediate frequency is zero. This avoids image frequency problems and the 3 dB penalty. But it needs to directly synchronize local laser and received signals. This entails some handicaps:

- Laser phase noise impact on overall receiver performances
- Penalty due to synchronization loop delay

Because of its high selectivity and tunability performances, homodyne optical systems are the optimum way to achieve narrow wavelength spacings; thus increasing fibre capacity. However, until now, these kinds of systems were believed to be complex and high cost solutions. That is the reason why they were only envisaged when regarding long-haul systems. Since 2004, a great effort has been done, reducing complexity. At present, homodyne ONUs are beginning to compete with other architectures.

An example can be the CPE proposed in [Bock06], shown in Fig. 4.28. It includes a PSK receiver architecture, based on time-switching phase diversity [Fabrega07]. It has experimentally demonstrated to be a first approach towards the low cost implementation of a reliable optical homodyne receiver, with a 1.8% linewidth/bit rate ratio tolerance operating in real time. Its principle of operation is quite simple: The optical phase modulator at the local laser output was controlled by the data clock (50% duty cycle) producing a fixed 0°–90° phase modulation, to obtain the Inphase (I) and Quadrature (Q) signal components, at the first and second half part of each bit time (T_b) respectively. Thus, properly processing the photodetector output signal, linewidths as high as 18 MHz could be tolerated while operating at 1 Gbps. The local laser was re-used in order to transmit upstream data, also PSK modulated. Thus, a symmetric receiver could be implemented at the side of the CO.

Homodyne ONUs can be used when upgrading already deployed dense WDM network architectures, towards ultra-dense ones. For example, the case of an

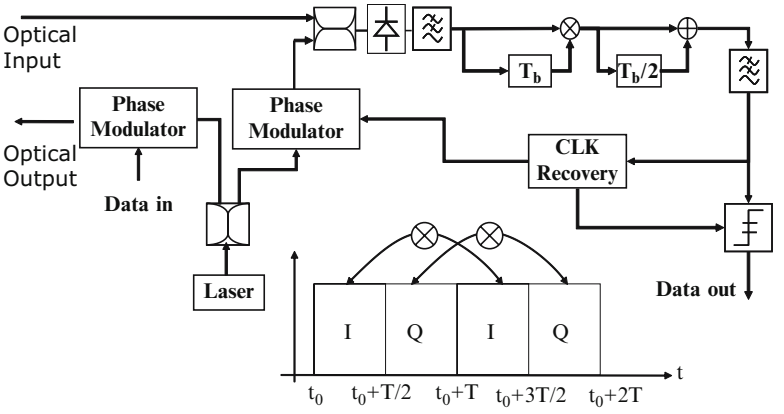

Fig. 4.28 Optical line terminal and customer premises equipment transmission module

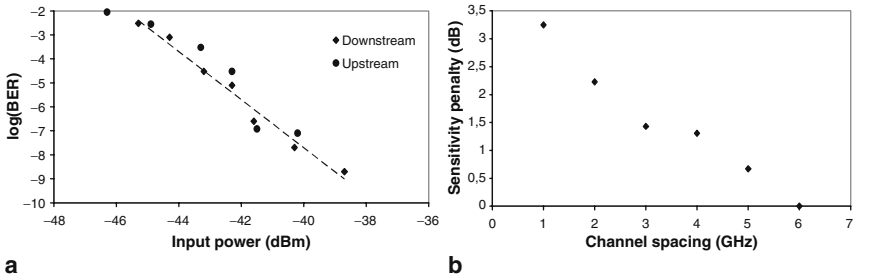

Fig. 4.29 (a) Up- and downstream transmission results; (b) sensitivity penalty as a function of channel spacing

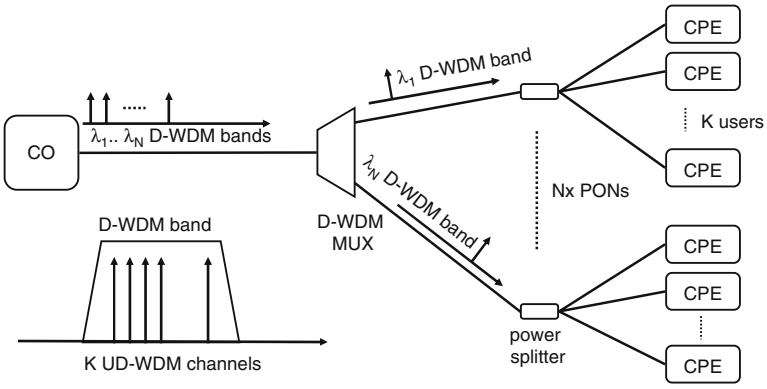

Fig. 4.30 Network outside plant; dense and Ultra-Dense WDM routing profile

outside network plant based on two splitting stages is considered. A classical dense WDM routing stage, routing a set of ultra-dense wavelengths to a secondary splitting stage, where a power splitter is placed and distributes the signal to each of the ONUs connected to the branch, is assumed. Each ONU receives the set of wavelengths that have been passed through the first WDM demultiplexer (typically a 1 × N AWG). Then, the tuneable local oscillator at the CPE selects the ONU's assigned channel and decodes downstream data by means of optical homodyning. The complete scheme of such network is shown in Fig. 4.30.

In terms of available bandwidth, the proposed network offers huge transmission capabilities. Using 2 GHz channel spacing and 1 Gbps data rate, 32 channels can be easily accommodated in an ITU-T (International Telecommunication Union) G.694.1 100 GHz DWDM channel. The penalty was measured to be less than 2.5 dB and the sensitivity was of −38.7 dBm, as shown in Fig. 4.29. For the C-band, 40-channel AWGs are commercially available so the network can potentially serve 40 × 32 = 1,280 users, offering a total capacity of more than 1 Tbps.

4.6 Active and Remotely-Pumped Optical Amplification

Recently standardized PONs for FTTH permits a splitting ratio up to 32 in case of EPON [IEEE802.3ah] and up to 64 users in Gigabit Passive Optical Network (GPON) [ITUG984.2], [Prat02]. This is mainly limited: on the one hand, by the bandwidth sharing level, on the other hand, by the splitter loss.

The increase of this split factor is of high interest nowadays, aiming to reduce the capital expenditure per user and to improve the scalability of the access network, also alleviating the fibre-exhaust situation in urban areas.

The bandwidth sharing limitation is overcome by faster transmitters and receivers providing higher bit rates. Using reflective devices, a WDM PON providing upstream bit rates at 5 Gbps has been demonstrated using a faster RSOA [Chanclou07]. Alternatively Reflective ElectroAbsorption Modulators (REAM) also provides higher bit rates (see Chapter 3); integration of SOA and REAM provides both high output signal power and high modulation bit rate [Kazmierski07].

Similar bandwidths can be provided to 128 users by sharing 5 Gbps among them or even to 256 users sharing 10 Gbps, than the usual bandwidth provided by distributing 1 Gbps among 32 users or 2.5 Gbps to 64 users.

The splitter loss is a second major limitation for increasing the splitting ratio. The insertion of active elements to the Access Network and especially optical amplification can provide a solution (Fig. 4.31). A first approach consists in incorporating optical amplifiers at the remote nodes of the access network [Davey05].

The optical amplification for overcoming the increasing splitting ratio can be provided by SOAs, EDFAs or any other, in general, rare-earth Doped fibre amplifier. The main advantage of using a SOA is that it can provide optical gain in long range of wavelengths, as this device essentially consists in a laser structure without mirrors.

Several research projects are working on different implementations of this technological approach. The European project PIEMAN [Davey06] implements the local exchange at 90 km from the OLT by using an EDFA and an AWG.

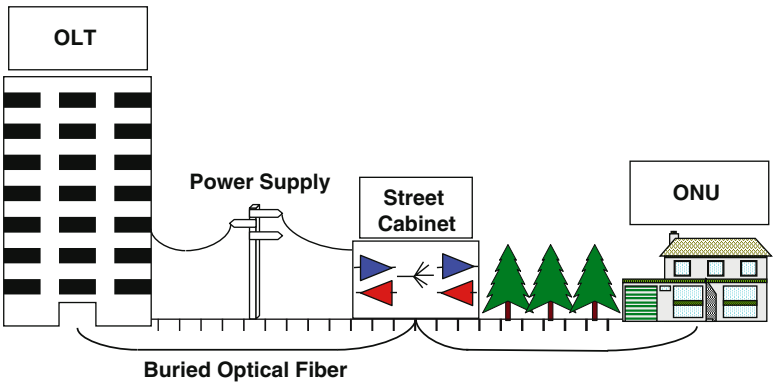

Fig. 4.31 A possible deployment of a PON including active optical amplification

Some other European projects as PLANET project [VandeVoorde97], and more recently the MUSE [Rasztovits07] also introducing electro-optical (EO) regenerators to compensate optical losses and other transmission impairments as well as providing aggregation functions.

This technical solution requires to provide a controlled environment and power supply to the remote nodes or local exchangers for the optical amplifiers, either SOA or optical fibre amplifiers. This can be done by building street cabinets for provisioning the adequate conditions. This means that the extended Access Network is no more a passive optical network in a strict sense, due to these electrical supply requirements.

An alternative approach for including optical amplification in PONs while maintaining the optical outside plan completely passive can be done by incorporating Erbium Doped Fibres (EDF), being remotely pumped, so that no power supply or controlled environment is required as shown in Fig. 4.32.

Following this alternative approach, several proposals have been done. One of the first ones was self-amplification [Suyama91], where lasers at OLT and ONU transceivers are used for both signal and pump functions and EDF could be either locally pumped at ONU terminal [Feuer95] or remotely [Feuer96]. This solution, also recently tested in GE-PON [Lee05], requires a tight control of the distributed pumping from ONUs to avoid pumping-power fluctuations at EDFs.

Another proposal of Super PON [Tan97], [VandeVoorde00] introduces pump lasers at the head-end for remote pumping of EDFs. This is a more convenient approach as it maintains the passiveness of the external plant; it only increases the cost of the shared OLTs and the consequent reduction of the TDM bandwidth per user can be compensated with the expected increase of the bit rate or by means of WDM.

Remotely pumped EDFAs have been previously demonstrated; a budged increase of 12 dB (11 dB with remote EDF + 1 dB with Raman) in a system with remote in-line has been shown, by means of experimental and theoretical investigation [Hansen97]; in [Blondel93], a 370 km repeaterless submarine transmission with 1,480 nm remote pump amplification is demonstrated. However, no systematic

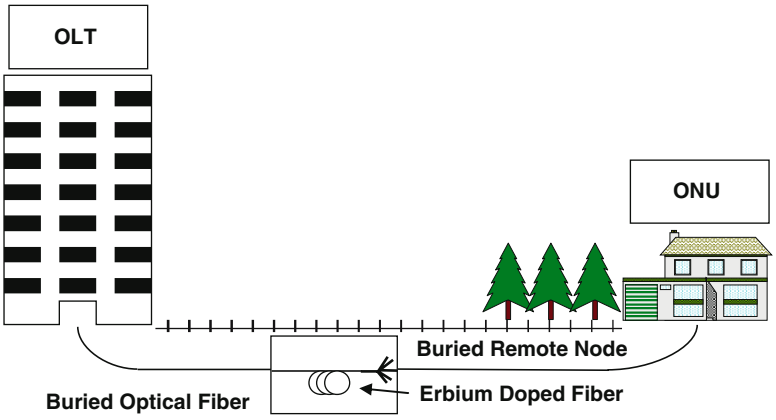

Fig. 4.32 A possible deployment of a PON including remote optical amplification

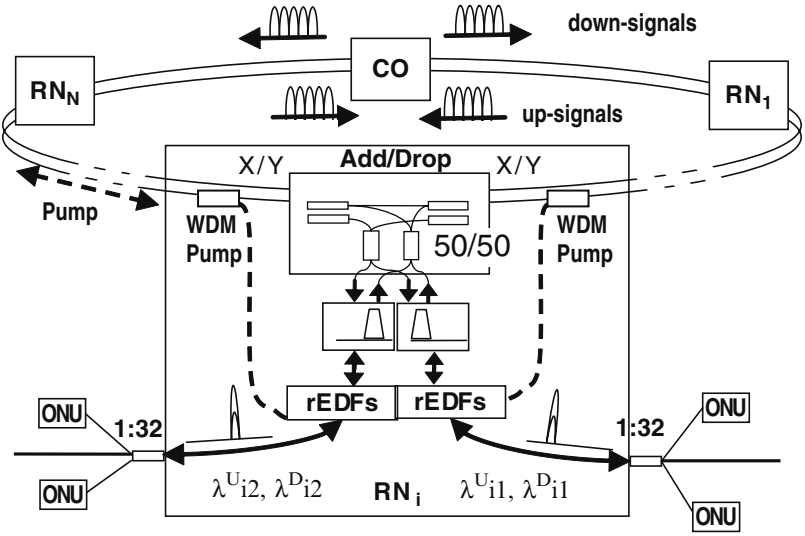

Fig. 4.33 Remotely pumped amplification implemented at the Remote Node of the Sardana network

study was done exploring optimal remotely pumped PONs configuration for maximal splitting ratio compatible with cost effective restrictions and OSNR (Optical Signal-to-Noise Ratio) quality requirements. Key aspects to be designed are the EDF location inside the splitter module and its length.

An example of the performance and implementation of remotely pumped amplification can be seen in Fig. 4.33. It shows the functional blocks of a passive Remote Node (RN) of the Sardana network [Lazaro07a] (see Chapter 7 for more details). The Sardana architecture provides in excess of 100 Mbps to more than 1,000 users along 100 km. Due to the large size of the access network, the link losses are much higher than already standardized PON networks, reaching values in the range of even 50 dB [Bock07]. In this case, optical amplification providing 20 dB gain allows using Class A/B/C equipment for the deployment of the network [Bock07].

The required optical gain is provided by a section of EDF, situated at the RN, and the required pump power is provided by 1,480 nm pump lasers situated at the CO and propagated through the optical fibres of the network till the EDFs of the RN. Several distribution methods can be used for providing the required pump power to each EDF. A simple, though non optimal procedure consists in reusing the excess pump power of the EDF to the fibre ring for reusing it at the next RN, thanks to the EDF characteristics and the low losses of currently commercial 1,480/1,550 multiplexers (of ~0.2 dB).

Figure 4.34a shows the measured gain curve and pump attenuation for 10.4 m length of EDF at pump powers varying from −25 to 16 dBm and small signal (−42 dBm). A pump power of ~4.8 dBm is required for transparency. At 16 dBm of input pump power, the gain saturates at ~15 dB (1.44 dB/m) and the pump attenuation coefficient decreases to 0.41 dB/m leading to a power consumption of 14 dBm

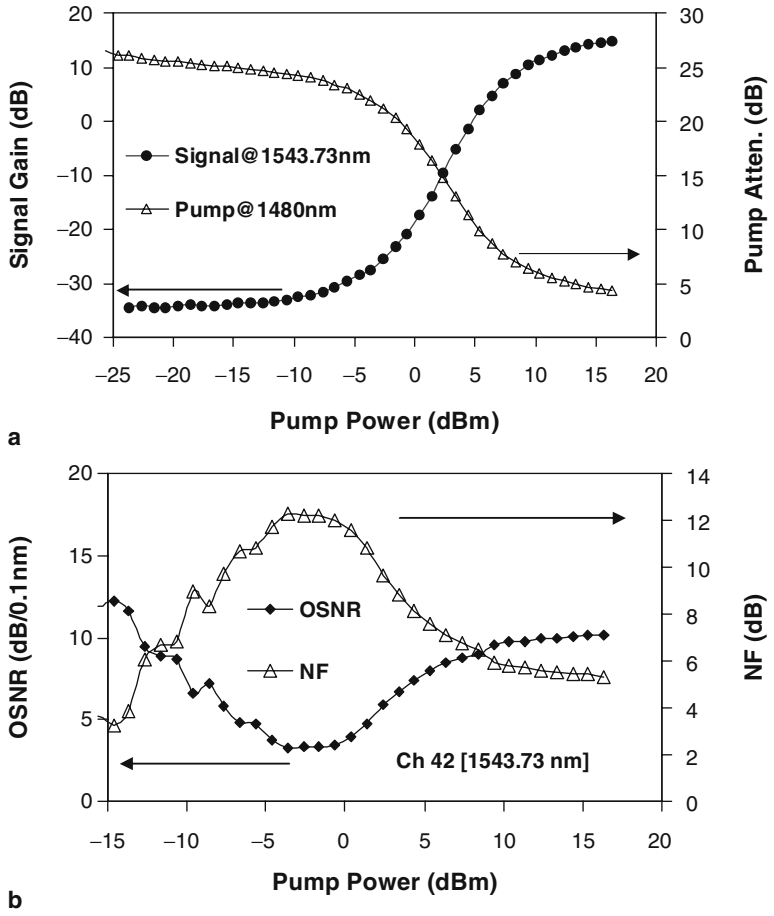

Fig. 4.34 (a) Measured small signal gain (ITU-T ch.42) and pump attenuation for 10.4 m of the HE980 Erbium Doped Fibre; (b) Optical Signal-to-Noise Ratio and Noise Figure

per EDF. The 3 dB gain reduction takes place at a pump power of 11 dBm. A reduction in the available pump power of the network would also reduce the Signal-to-Noise Ratio (SNR).

Figure 4.34b shows the measured OSNR for an optical bandwidth of 0.1 nm. The Noise Figure (NF), signal-spontaneous-emission contribution, is calculated from the OSNR values using:

$$NF_{dB} = P_{S_in,dBm} - OSNR_{dB} - 10\log_{10}(h\nu\Delta\nu)_{DBm} \tag{4.3}$$

which can be deduced from [Desurvire02] and where NF_{dB} is the NF expressed in decibels, $P_{s_in,dBm}$ is the input signal power expressed in decibels, $OSNR_{dB}$ is the OSNR value measured in decibels within an optical bandwidth of 0.1 nm, and

$10\log_{10}(h\nu\Delta\nu)_{dBm} \approx -58\,dBm$ [Desurvire02] for the same optical bandwidth and near a wavelength of 1.55 µm.

At high-pump-power levels, a NF of 5.3 dB has been measured in forward pumping configuration. At the 3 dB gain reduction point of 11 dBm, a small increase of the NF to 5.7 dB is observed.

Also the EDF's length dependency of gain and NF is important information for the optimization of the remote amplification in an access network.

Figure 4.35a and b show the measured gain and OSNR curves of HE980 EDF respectively. Also in Fig. 4.35 it can be seen that transparency is near 5 dBm of pump power for all set of lengths and signal gain seems to saturate at about 16 dBm of pump power.

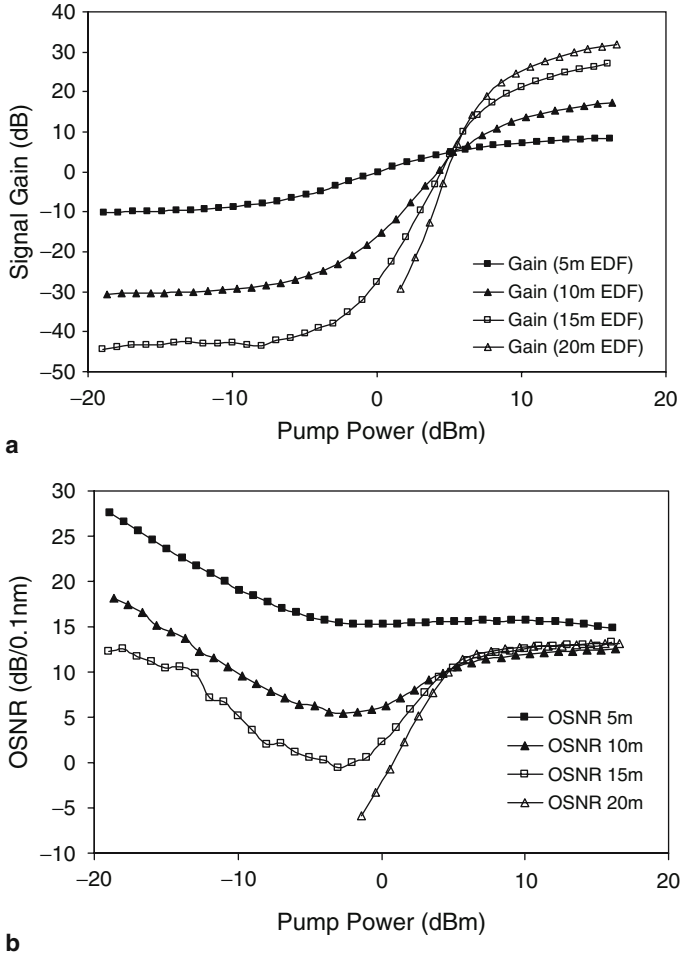

Fig. 4.35 Dependencies on the length of the Erbium Doped Fibre: (a) small signal gain; (b) measurements of the Optical Signal-to-Noise Ratio

The NF is defined as the ratio of the signal to noise ratio at the input of the amplifier to that at the output of this, $NF = SNR_i/SNR_o$. The usual expression for SNR at the input of the amplifier is computed assuming that the signal detection main limitation is shot noise, therefore $SNR_i = P_{in}/(2h\nu B_e)$ [Becker99], where P_{in} is the optical power at the input of the amplifier, hν is the energy of photon and B_e is the bandwidth of the electrical filter used in the electrical receiver circuit. The SNR at the output of the amplifier is $SNR_o = (GI_s)^2/(N_{s\text{-}sp} + N_{sp\text{-}sp} + N_{shot})$ [Becker99], where G is the gain of the amplifier, I_s is the photocurrent generated by the signal photons, $N_{s\text{-}sp}$ and $N_{sp\text{-}sp}$ are the signal-spontaneous and spontaneous-spontaneous noise powers respectively, and N_{shot} is the shot noise power.

Usually only $N_{s\text{-}sp}$ is used to calculate NF of the Optical Amplifier, following [Becker99] Eq. (4.4) is obtained:

$$NF = \frac{P_{ASE}}{h\nu\Delta\nu G} \tag{4.4}$$

where P_{ASE} is the ASE power and Δν is the resolution bandwidth of the optical spectrum analyzer, in our case 0.1 nm. Nevertheless, other terms that are usually dismissed could lead to significant NF variation. If we add the N_{shot} and $N_{sp\text{-}sp}$ contribution to Eq. (4.4), we obtain Eqs. (4.5) and (4.6) respectively:

$$NF = \frac{P_{ASE}}{h\nu\Delta\nu G} + \frac{1}{G} \tag{4.5}$$

$$NF = \frac{P_{ASE}}{h\nu\Delta\nu G} + \frac{1}{G} + \frac{P_{ASE}{}^2(2B_o - B_e)h\nu}{4(h\nu\Delta\nu)^2 G^2 P_{in}} \tag{4.6}$$

where B_o is the optical bandwidth of the filter at the output of the EDF or at the input of the ONU.

Using Eqs. (4.4)–(4.6) on the measurements from Fig. 4.35, the results depicted in Fig. 4.36 can be achieved.

Figure 4.36a and b show that using Eq. (4.6) with levels between 5 and 16 dBm for the pump power, NF achieves values near 3 dB for 5 m EDF and 5 dB for the 15 m EDF respectively. When we use Eq. (4.7) considering $N_{s\text{-}sp}$ and N_{shot}, or Eq. (4.6) considering $N_{s\text{-}sp}$, N_{shot} and $N_{sp\text{-}sp}$ using a narrow optical bandwidth, for example 50 GHz, the results are practically the same achieved with the usual expression Eq. (4.6). Nevertheless, when no optical filter is used at the output of the EDF or the input of the ONU, NF increases in a margin of 10 dB, using Eq. (4.6). This fact is due to the dependence on the bandwidth of the optical filter (B_o) in the third term of Eq. (4.6). In consequence, the usual way to calculate NF could not fit well the real behaviour in some special cases, like a missing optical filter at the output of the EDF.

Also in Fig. 4.36a and b it can be seen a significant different behaviour of the NF at very low pump levels using the different expressions. Figure 4.36a and b show that the NF calculated by using the usual expression in Eq. (4.4) (represented by NF(1) in Fig. 4.36), which considers only the $N_{s\text{-}sp}$ contribution, tends to very small values. This behaviour can be explained using a similar expression of Eq. (4.4).

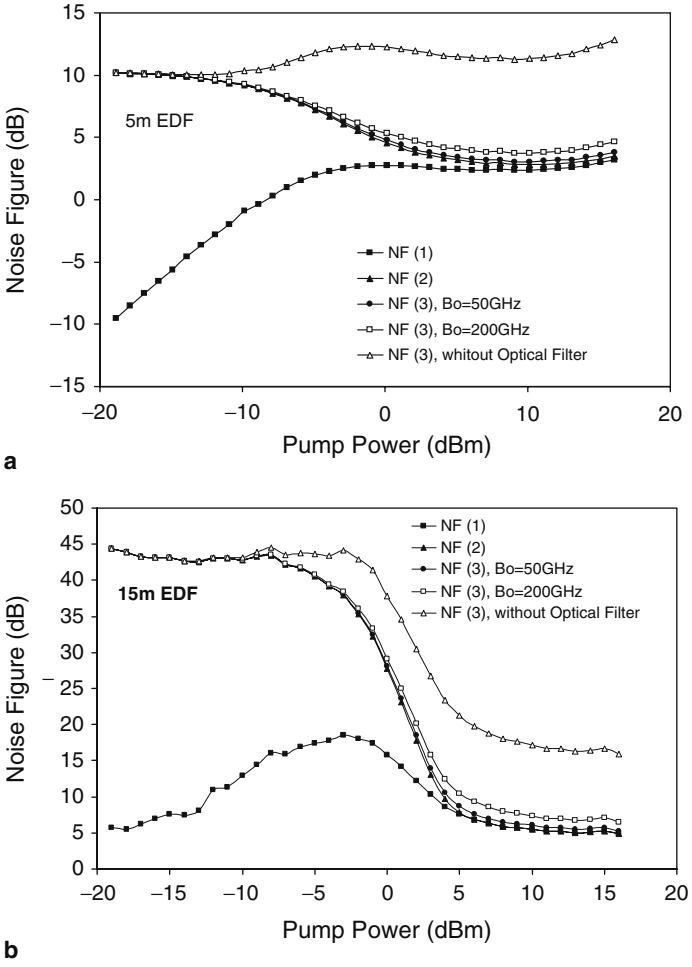

Fig. 4.36 Noise Factor due to Eqs. (4.4)–(4.6) at different optical bandwidths of 50, 200 GHz and all C-band (without optical filter), $B_e = 2$ GHz, Δl equivalent to 0.1 nm: (a) for 5 m and (b) for 15 m Erbium Doped Fibre

In order to obtain an equivalent expression of Eq. (4.4), we have to define the normalized population inversion parameter n_{sp}, defined as $n_{sp} = N_2/(N_2-N_1)$, where N_2 is the normalized population density in the upper state and N_1 is the normalized population density in the lower state of the Erbium ion transition that is responsible of the optical amplification.

As it can be seen in Fig. 4.37, in case of a very low pump power all ions are in the lower state N_1 so that $n_{sp} = 0$. Otherwise, for very high pump powers, nearly all ions are in the higher state N_2 and therefore $n_{sp} = 1$.

Using the relationship $P_{ASE} = 2n_{sp}h\nu\Delta\nu(G\text{-}1)$, we can obtain an equivalent expression of Eq. (4.4) used to explain these anomalous behaviours.

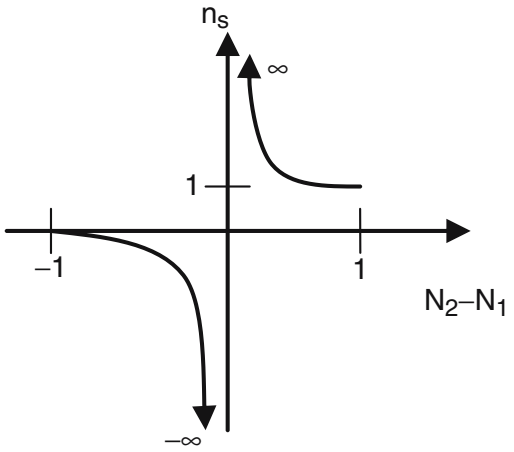

Fig. 4.37 Representation of the behaviour of the normalized population inversion parameter

$$NF = 2n_{sp}\frac{(G-1)}{G} \tag{4.7}$$

Figure 4.37 shows that if $N_2 \approx N_1$, n_{sp} tends to ±&infinity;, that is the reason for the NF(1) peak near 0 dBm of pump power showed in Fig. 4.36a and b. Due to the relationship between n_{sp} and gain which is $G = [P_{ASE}/(2n_{sp}h\nu\Delta\nu)] + 1$, although n_{sp} take negatives values, NF(1) will be always positive because (G-1) will have the same sign as n_{sp}.

The other anomalous fact to analyze from Fig. 4.36a and b using Eq. (4.4), is the behaviour of NF(1) at very low pump levels. Figure 4.36a shows that for 5 m EDF, NF(1) tends to very small values, negative in logarithmic scale, in accordance with the very high OSNR values show in Fig. 4.35b for those pump powers. Otherwise, in Fig. 4.36b it can be seen that for 15 m EDF NF(1) decreases slower and reaches a constant value. This is due to the behaviour of n_{sp} versus gain.

Figure 4.38a and b show the different behaviour of gain and n_{sp}, obtained with $n_{sp} = P_{ASE}/[2h\nu\Delta\nu(G\text{-}1)]$, as a function of pump power for two different lengths of EDF.

It can be seen in Fig. 4.38a that for 5 m EDF, signal gain tends to −10 dB, in logarithmic scale, behaving as an attenuator. On the other hand, n_{sp} tends to zero so that NF is tending to small values because the dominant term is n_{sp}.

Figure 4.38b shows that for 15 m EDF the gain tends to −44 dB and n_{sp} tends to a similar value, therefore NF reaches a constant value as it can be seen in Fig. 4.38b.

Figure 4.38a and b show that using Eqs. (4.5) and (4.6) this anomalous behaviour shown by using Eq. (4.4) at very low pump levels is corrected. The dominant term at low pump levels is N_{shot} and as we have seen, the $N_{s\text{-}sp}$ contribution tends to zero. Due to that, NF using Eqs. (4.5) and (4.6) tends to 1/G, as the EDF behaves as an attenuator.

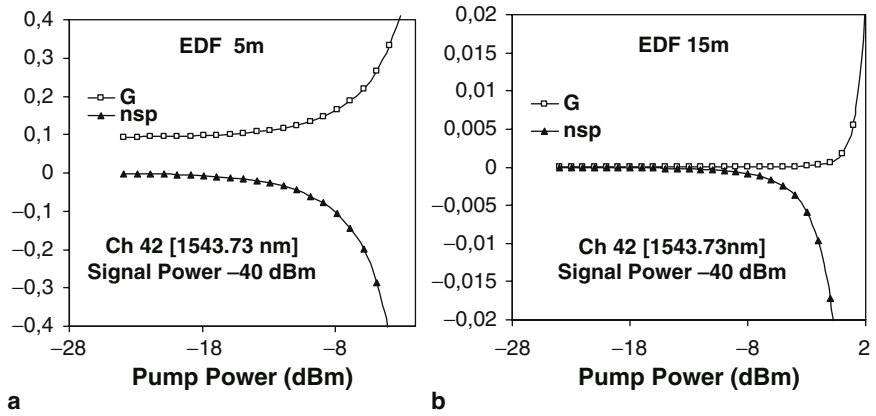

Fig. 4.38 Gain versus normalized population inversion parameter

4.6.1 Burst Traffic

Access PONs face the added problem of the bursty traffic in the upstream direction. The data frame is divided into short slots, one for each user, transmitting at a specific power level within a wide margin specified, also with short guard times. The burst time is comparable to the time constants of the Erbium states and thus the gain variation distorts the envelope of the bursts. Moreover, the newly applied Dynamic Bandwidth Allocation algorithms in PONs with variable slot times introduce a harder requirement to the optical amplification transients. A lot of research has been done on the dynamics of the EDFA under power transients [Tian03], also with proposals for different stabilization techniques.

4.6.2 Raman Amplification in PONs

In section 4.1 we pointed out that WDM transmission systems with huge number of signal channels have been recognized as the best way to construct large capacity optical transport networks. The available number of channels in WDM transmission systems has been limited by the gain bandwidth of optical amplifiers. Exploitation of wide-band optical fibre amplifiers and new working bandwidths such as S-, L- and U-bands are therefore indispensable key devices and approaches for future optical networks. In particular, the high gain required for longer spans or high splitting ratios (as in long reach, multi end-users PON architectures) is inevitably better accompanied by distributed amplification like Raman instead of a lumped one. Furthermore, in this last case the optical network would not be still considered fully passive.

It must be pointed out that the increased penalties of associated intrinsic phenomena, for example the Rayleigh backscattering, can be present when a high Raman pump power is used. Rayleigh effects can stem either from double Rayleigh backscattering (DRS) or from discrete reflection of the forward propagating signal followed by Rayleigh backscattering (RS) [Kobiakov03]. The DRS has been studied by many authors [Kobiakov03], [Tsujikawa00], [Essiambre02], modelled and characterized [Park04]. It is known that the process is a result of multiple reflections of light inside the fibre. To achieve a complete control on the randomly lasing action induced by the DRS, a set of FBG's can be introduced before the fibre, and these will reflect back already reflected power at specific wavelengths. These reflected wavelengths will seed the DBS spontaneous lasers and force the lasing to occur at the FBG wavelengths [Teixeira05] inducing multiple cascaded Raman amplification. This concept will not be part of this subchapter but still represents a way to implement distributed amplification in other areas (L- and U-band) via a single standard Raman pump for C-band applications.

In Fig. 4.39 an experimental setup able to perform a standard Raman amplification in the C-band by means of an optical fibre and a Raman pump is sketched.

In particular, a multiple Raman pump (RP) consisting of three Keopsys Raman fibre lasers able to work in single mode at 1,428 nm or multiple mode at 1,428, 1,445 and 1,466 nm, has been used to induce Raman amplification in two different kinds of optical fibres: a standard dispersion shifted fibre (DSF) and a DCF. A cascade of isolators and a 10 dB attenuator limit impairments and possible damages due to high pump power to both an ECL and an optical spectrum analyzer.

As it can be noticed from Figs. 4.40 and 4.41, the Raman pump which is not suitable for operational mode in the full S-band, is still able to guarantee a minimum of gain at wavelengths where the EPON system is still able to operate (1,505–1,520 nm).

Figure 4.42 represents the investigated configuration adopting a distributed amplification inside the EPON test-bed. The signal coming from the OLT is coupled via a WDM coupler to the Raman amplifier. The RP has been connected in a counter propagating way via a second WDM coupler.

Performances are shown in Fig. 4.43a for the throughput from PC 100 to PC 101, PC 102 and PC 103. Figure 4.43b shows throughput performances from PC 101, PC 102 and PC 103 to PC 100.

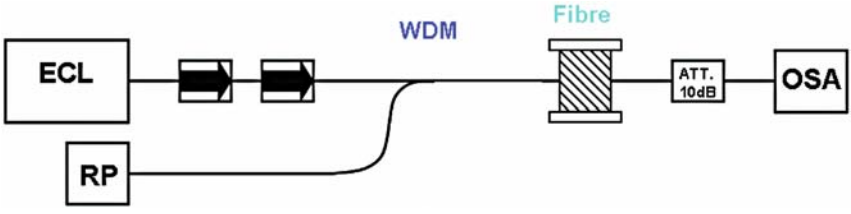

Fig. 4.39 Setup to achieve Raman amplification

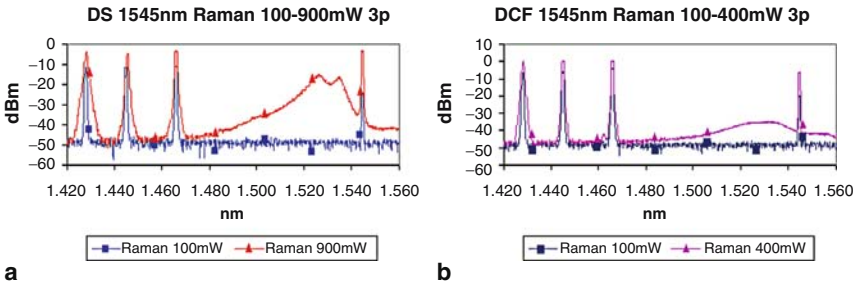

Fig. 4.40 Output optical spectra for (a) a Dispersion Shifted Fibre, and (b) a Dispersion Compensation Fibre

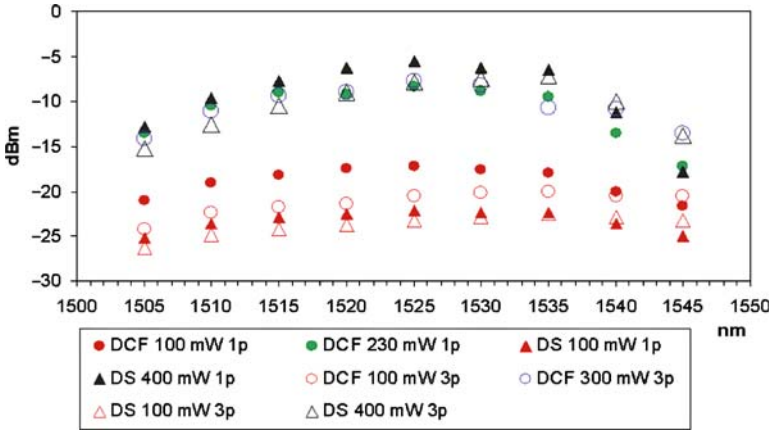

Fig. 4.41 Comparison between Dispersion Shifted and Dispersion Compensation Fibre in a wavelength range from 1,505 to 1,550 nm

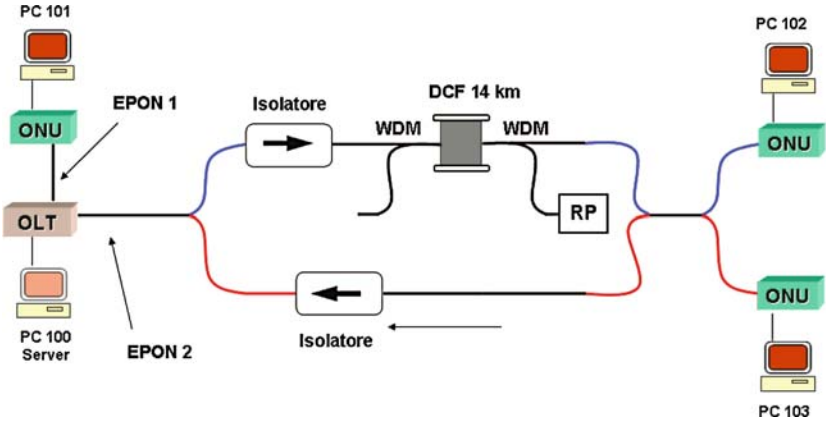

Fig. 4.42 Experimental setup with Raman amplification in the C-band

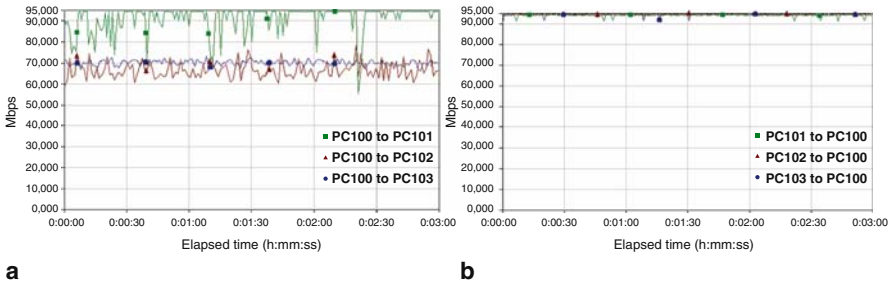

Fig. 4.43 Throughput performances adopting a distributed amplification inside the EPON test-bed

4.6.3 Remote Powering

In a passive optical network, some functionality like protection, wavelength selection or link budget optimisation needs active device. In order in maintain the passive property of the network, the remote powering by the optical fibre offers this possibility. The key element of this system is a pigtailed Power Converter Module (PCM) [Werthen96]. The PCM converts optical power carried in the fibre into electrical power to activate the active devices in the infrastructure. The output voltage and current depend on the optical power injected into the module. The maximal output voltage is about 5 V whereas the output current varies between 1 and 60 mA for an injected light in the range of [+1, 23] dBm.

4.7 Variable Splitter, Variable Multiplexer

The typical PON [Nakamura04] connects a single fibre from an OLT to multiple ONUs. The OLT usually resides at CO whereas the ONUs are installed on or near the subscriber's premises. The point-to-multipoint connectivity between OLT and multiple ONUs is obtained using one or more passive and Fixed Optical Splitters (FOS) in the fibre path.

In this context, Variable Optical Splitter (VOS) is an advanced component which can integrate access PON in the future. This active component with tuneable coupling ratio can be used to optimize the optical budget in function of the budget topology.

Figure 4.44 below shows an access PON design with 64 subscribers according to the ITU-T G.983.1 standard. The Distribution Frame (DF) allows sharing of optical power for each subscriber. The base DF (DF_b) is implemented in the network centre and the other Distribution Frames (DF_m) are placed near each ONU. Each DF_m is adapted to the subscriber number and made up of different couplers (1 × 8, 1 × 16 and 1 × 32). DF_b contains one fixed or variable 1 × 4 optical splitter. The splitter is achieved by cascading three 1 × 2 optical couplers. The injected light into the 1 × 2

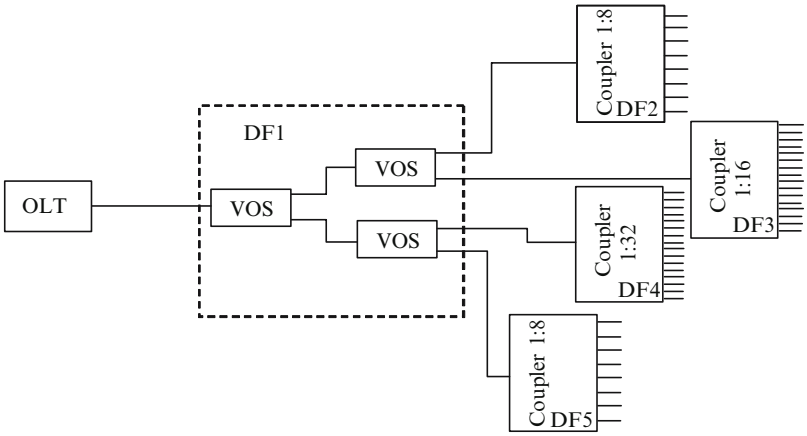

Fig. 4.44 Access PON architecture with Fixed or Variable Optical Splitter

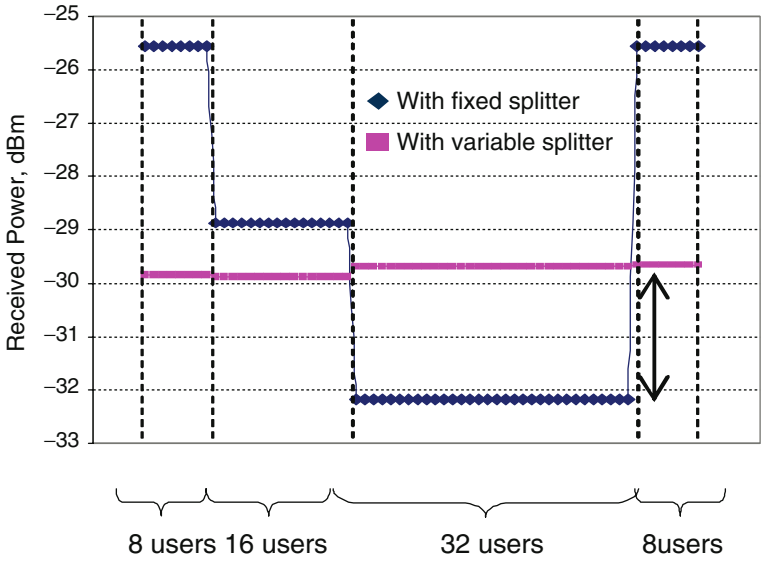

Fig. 4.45 Optical power received by each optical network unit

VOS is transmitted through two output fibres with a tuneable ratio respectively from 99% to 1% and from 1% to 99%. The component is activated by applying an electrical power and fabricated with a magneto-optical technology [Wada02]. The 1 × 2 FOS presents an optical loss of 3.3 dB whereas about 3.7 dB of losses are measured in the 1 × 2 VOS at a coupling ratio of 50–50%.

The time graph (Fig. 4.45) represents a comparison of the optical power received by each ONU for a PON topology using 1 × 4 fixed (F) or variable (V) coupler in

the DF_b. Using 1 × 4 FOS, 32 ONUs are close to the detection boundary with a received optical power of about −32.2 dBm. The use of the 1 × 4 VOS allows equalizing of the light received by all ONUs at about −29.8 dBm. An optical budget gain of about 2.4 dB is then obtained. With this gain, the subscriber number can be increased or one can connect ONUs at about 10 km farther. Moreover, the gain also allows insertion of varied optical components such as switch, filter or attenuator in order to make a reliable network.

Chapter 5
Network Protection

Jiajia Chen, Miroslaw Kantor, Krzysztof Wajda, and Lena Wosinska

The significance of broadband and multimedia telecommunications is still increasing and the use of fibre-optic technology in the access network is growing very fast in order to meet customers demand. Along with the higher bandwidth demand, increasing number of subscribers, and advances in the Wavelength Division Multiplexing (WDM) device technology, the WDM Passive Optical Network (PON) and hybrid WDM/TDM (Time Division Multiplexed) PON has been considered as a next generation solution for the broadband access. Meanwhile, in order to meet Service Level Agreement (SLA) and guarantee the appropriate level of connection availability, fault management within any type of the PONs becomes more significant for the reliable service delivery and business continuance. Connection availability is an issue of deep concern to network operators since failure of any access network component, and thus interruption of their services, could result in significant losses of revenue.

This chapter reviews some protection schemes in PONs and provides reliability performance evaluation for the considered architectures. A customer typically expects the end-to-end service availability at least at the same level as that provided by the traditional copper based systems. Thus, before investing in a new technology network operators need to make sure that it will not degrade the service quality perceived by the customers.

To avoid misunderstanding we provide the set of definitions used in this chapter. Next, we review the protection schemes in PONs and follow with the reliability analysis and performance evaluation. Finally, we draw some conclusions.

5.1 Definitions

- We define **protection** as the use of pre-assigned capacity between nodes to replace a failed transport entity. Three fundamental types of protection mechanisms are: 1 + 1, 1:1 and 1:N protection (so called shared protection).
- **Link protection** is the mechanism that automatically switches the traffic from the failed fibre to a dedicated protection path connecting the end nodes of the failed fibre.

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- **Path protection** is the mechanism that automatically switches the traffic from the failed path through a dedicated path. The protection path should preferably be link and/or node disjoint with the working path (so called diverse protection).
- **Reliability function** *R(t)* is the probability that a component (system) will survive until a time instant t (i.e., a failure occurs after t)

$$R(t) = P(X > t) = 1 - F(t),$$

where X is a positive, continuous random variable referred to as a lifetime, describing time of failure-free operation and $F(t)$ is a lifetime distribution. The reliability function can also be seen as a probability of failure-free operation during a specified period of time $(0 - t)$.

- **Failure rate** refers to exponentially distributed lifetime and corresponds to the mean number of failures occurring in a time unit. Typically, failure rate is given in FITs (Failures in Time) where 1 FIT corresponds to one failure during 10^9 h. Failure rate is most common reliability parameter of components and is used as input data for reliability performance evaluation of systems consisting of these components.
- **Mean Time To First Failure (MTTFF)** is referred to as an expected value of the random variable X (lifetime) and also corresponds to **Mean Up Time (MUT)**.
- **Mean Time To Repair (MTTR)** is an expected value of a random variable corresponding to the time needed to repair or replace the failed component/system. MTTR corresponds to **Mean Downtime (MDT)**.
- **Mean Time Between Failures (MTBF)** is a sum of mean uptime and mean downtime. MTBF = MTTFF + MTTR.
- Asymptotic **availability** is the probability that, in the steady-state, the system is operating at any time. This probability is called also the steady-state availability and is denoted by **A**.
- Asymptotic **unavailability** is the probability that, in the steady-state, the system is failed at any time. This probability is also called the steady-state unavailability and is denoted by **U**.
- **Connection availability** is the probability that, in the steady-state, there is at least one optical path available between the considered network ports. This probability is called the steady-state availability, or the asymptotic availability of the connection. Connection failure is defined as a call loss due to failure of system components.
- **Reliability block diagram (RBD)** is a graphical representation of a system reliability model and is based on the functionality of the system. It illustrates the effects of all possible configurations of functioning and failed components on the functioning of the system. The reliability block diagram is, of course, obtained from the definition of the system failure. Each block in the diagram represents either a component or group of components that has two functional states: operating or failed. A characteristic parameter for each block in the

diagram is either the failure rate or asymptotic availability. The diagram is considered to have an input node at the left hand side of the diagram and an output node at the right hand side of the diagram. The system is functioning if there is at least one path in the diagram that runs from input node to output node and does not pass through a failed component.

5.2 Protection Schemes

As the requirements for service bandwidth increase in the broadband access network, it becomes more and more important to protect against access network equipment failures. To meet this demand, several protection architectures have been proposed for PON networks.

5.2.1 Standard Schemes

In PON architectures, an Optical Line Terminal (OLT) module is connected with multiple Optical Network Units (ONUs) by a passive Optical Distribution Network (ODN). To establish such point-to-multipoint connectivity, a passive optical splitter is used. Generally, the OLT is located in a central office and delivers the interface between the access network and the service node. In [ITU983], ITU-T (International Telecommunication Union) defined four types of standard network protection architectures for PONs. These architectures are referred to as, respectively, Type A, B, C, and D. They are reviewed in this section. First, the basic architecture without protection is presented in Fig. 5.1.

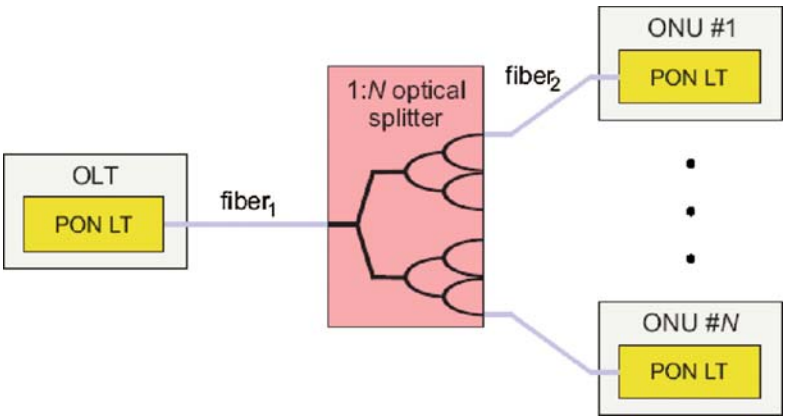

Fig. 5.1 The basic architecture: no redundancy

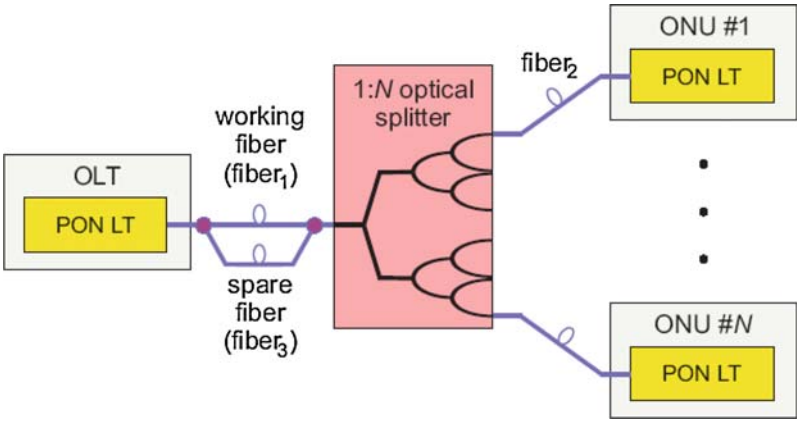

Fig. 5.2 Type A architecture: duplicated feeder fibre

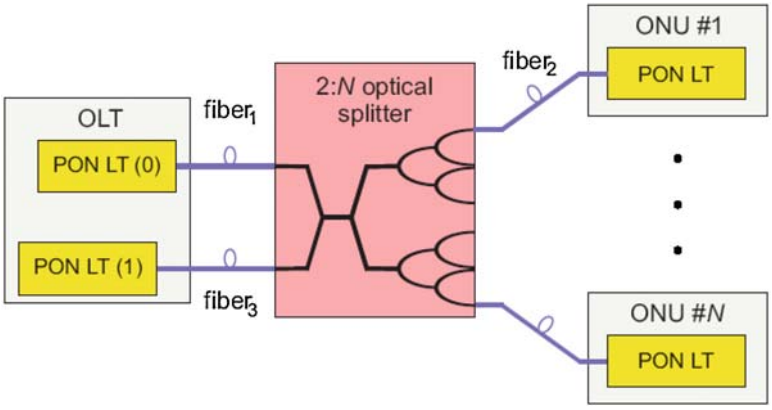

Fig. 5.3 Type B architecture: feeder fibre and line terminal at Optical Line Terminal are duplicated

In Type A architecture (Fig. 5.2) only the feeder fibre (FF) is protected. Since the protection switching is only applied to the optical fibres, no switching protocol is required for OLT/ONU in this scheme. In such a case, a fibre switch and PON TC (Transmission Convergence) protocols, such as ranging (upstream delay control), are controlled independently. The TC layer performs the re-ranging procedure after failure detection and optical switch recovery. The repeated procedure of determining upstream delay, i.e. re-ranging, is necessary as the distance between OLT and ONUs changes because the spare fibre length is significantly different from the working one. In this case, the signal loss or even cell loss is unavoidable in the switching period.

Type B architecture (Fig. 5.3) duplicates equipment between the OLT and the first splitter. The splitter has two input/output ports on the OLT side. The primary line terminal (LT) is normally working while the secondary one is used as a cold

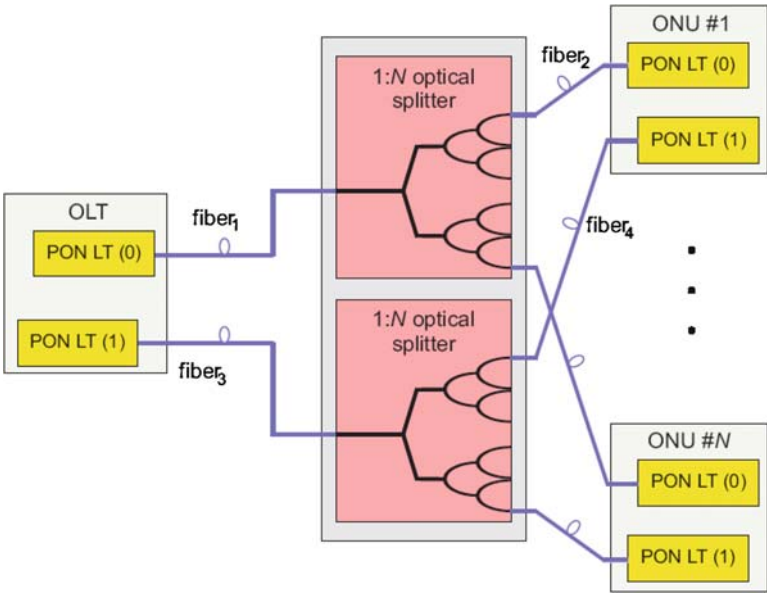

Fig. 5.4 Type C architecture: 1 + 1 path protection

standby. In case of the FF cut or the working line card failure, the backup is activated to restore service. Switching control is entirely executed by the OLT side, thus there is no need to define a switching protocol. Also in this case, like in Type A architecture, the re-ranging procedure should be executed.

In Type C architecture (Fig. 5.4) the PON equipment is fully duplicated providing 1 + 1 path protection. Both the primary and secondary interfaces are normally working (hot standby) and therefore the switching time can be very fast. Switching is performed at the TC layer for each individual ONU. Hitless switching (without cell loss) is also possible in this configuration.

Type D architecture (Fig. 5.5) allows for a partial duplication of resources on the ONU side. This means that independent duplication of distribution fibres (DFs) and FF is possible. The configuration enables the operator to deliver services for users with different reliability parameters. Concerning OLT, the characteristics of Type D architecture are the same as in Type B architecture. This type of protection cannot offer fast switching but provides all ONUs with some level of protection.

5.2.2 Novel Schemes

The optical access network is an emerging technology and new protection schemes are encouraged. Compared with transport networks, access networks are very cost sensitive because only a few subscribers need to share all the cost associated with

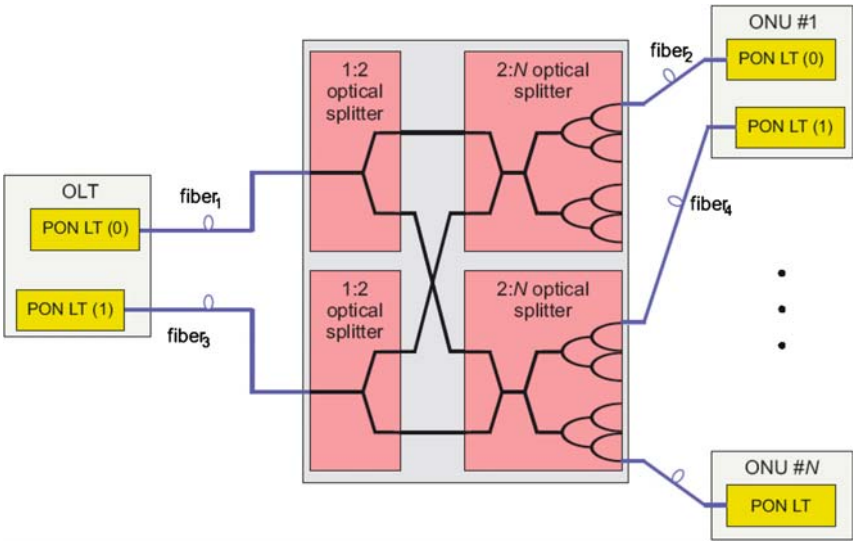

Fig. 5.5 Type D architecture: full/partial protection

the protection. Therefore, minimizing the cost for network protection and at the same time obtaining an acceptable level of connection availability is an important challenge. Here, some selected novel protection schemes for TDM, WDM and hybrid WDM/TDM PON are reviewed.

5.2.2.1 TDM PON

Figure 5.6 shows novel 1:1 dedicated link protection architecture proposed in [Chen06]. Between the OLT and the Remote Node (RN), two geographically disjoint fibres exist to provide dedicated protection against the FF cut. At the other end of the DFs, every two adjacent ONUs form a pair to realise dedicated protection. Each ONU contains an optical switch (OS) to initiate recovery from the DF failure. We refer to Fig. 5.6 where ONU Pairs 1 (ONU_1 and ONU_2) and $N/2$ (ONU_{N-1} and ONU_N) illustrate the self-protection principle. If there is no failure of the fibre link between ONU and the RN (see ONU $Pair_1$ in Fig. 5.6), the OS at ONU is set to its port 1. For the upstream, the traffic flow of ONU_1 goes through the OS and the first output port of the RN. In this case the fibre interconnecting ONU_1 and ONU_2 is not used. If the fibre break occurs between ONU and the RN (see ONU $Pair_{N/2}$ in Fig. 5.6), ONU_{N-1} will detect first the loss of the downstream signal power, since the transmitter at the OLT keeps sending digital-modulated light. An electrical control signal will then be generated to trigger the OS from port 1 (for the normal state) to port 2 (for the protection state) as shown in the figure. Thus, the corresponding interconnection fibre between port 2 of the OS in ONU_{N-1} and the Nth output of the RN works for both the upstream and downstream traffic flows associated with

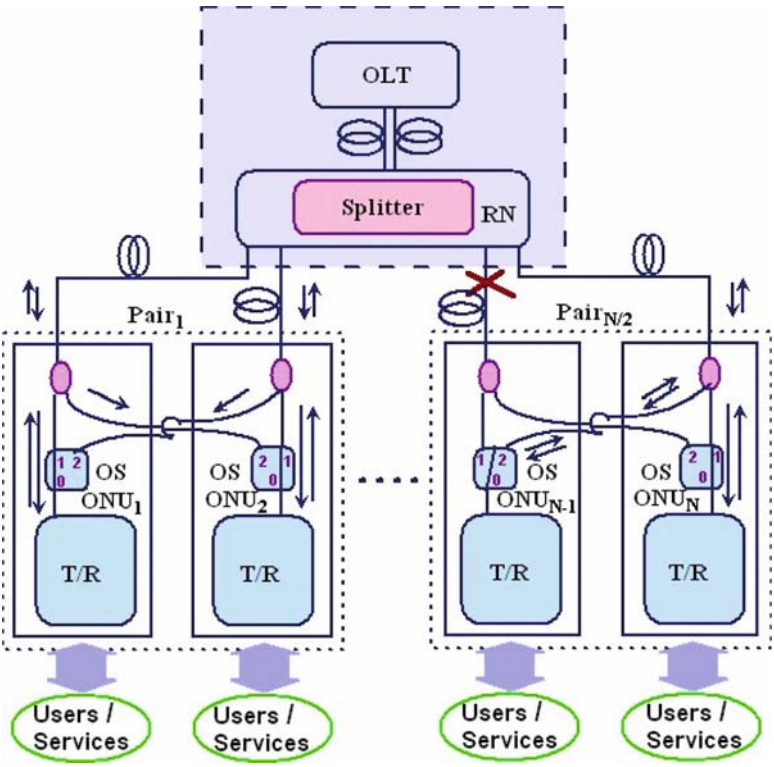

Fig. 5.6 Novel 1:1 link protection scheme for TDM PON

ONU_{N-1} (and ONU_N). ONU_N is protected in a similar way through the protection fibre connecting port 2 of the OS in ONU_N and the *N*-1st output of the RN.

It should be pointed out that this protection architecture is much more cost efficient than Type C while providing the same level of connection availability [Chen07].

5.2.2.2 WDM PON

In the protection architecture proposed for WDM PONs [Chan03] (see Fig. 5.7a), the RN comprises a $1 \times M/2$ Arrayed Waveguide Grating (AWG) (with $M = 8$) and uses 1 × 2 couplers to route the wavelengths to the ONUs. There are four wavelengths in each of the wavebands A, B, C and D as free-spectral range (FSR) passing through the same port of the AWG. Wavebands A and B are referred to as the Blue Bands while wavebands C and D as the Red Bands (see Fig. 5.7a). Two of the wavelengths in the wavebands A and C are for upstream, and the other two B and D are for downstream. Each odd ONU (ONU_{2i-1}, $i > 0$) receives the traffic carried by wavelength B_i, while wavelength D_i is removed by Red/Blue filter. Similarly, each even ONU (ONU_{2i}) receives the traffic at wavelength D_i while wavelength

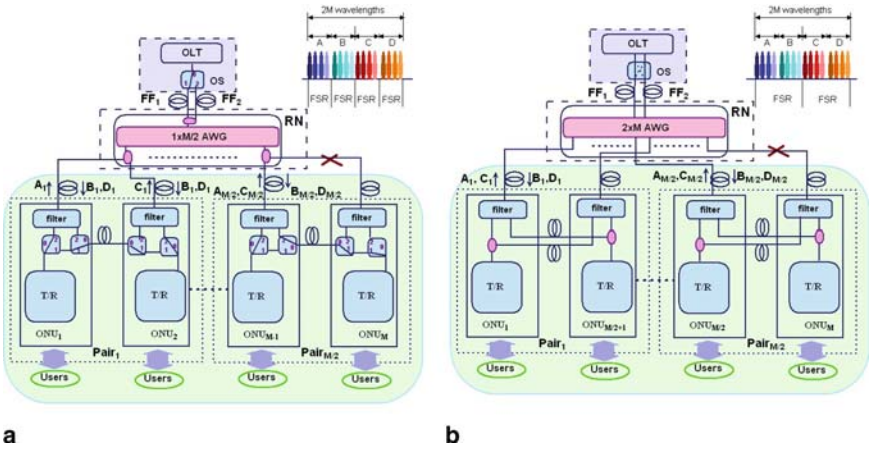

Fig. 5.7 Novel protection schemes for WDM PON

B_i is removed by Red/Blue filter. The OLT and the RN are connected by a single working FF_1 and a (geographically disjoint) single protection FF_2. Automatic protection switching is performed at the OLT. The ONUs can detect DF failures and control the OS status to realise the neighbouring protection.

Figure 5.7b depicts a centrally controlled protection architecture for WDM PONs with a $2 \times M$ AWG in [Wang05]. It includes two optical isolators in the OLT for the upstream and downstream traffic, respectively, and a 2×2 switch located in front of the FF_1 and FF_2 (see Fig. 5.7b). The decision circuit is moved to the OLT end to detect DF failures and to activate the wavelength rerouting mechanism to provide protection by setting the switch to the cross state.

Wavebands A and B in the blue band as one FSR are allocated for the downstream and upstream wavelength channels of ONUs from 1 to $M/2$, respectively, while wavebands C and D as the other FSR in the red band are for ONUs from $M/2$ to M, respectively. In normal operation mode, the FF_1 and FF_2 are used to carry the downstream and the upstream traffic, respectively while in the protection mode FF_1 becomes the upstream path while FF_2 becomes downstream path. Compared with the previous one, its requirements on the network resources (especially for each ONU) are greatly reduced, though it can not provide protection for FF failures and influence the other normal ONUs when the centrally controlled protection starts.

5.2.2.3 Hybrid WDM/TDM PON

Figure 5.8 shows the novel protection schemes for hybrid WDM/TDM PON in [Chen07]. For the protection of FF failures, the backup fibre is assumed to be geographically disjoint with the primary FF in order to provide diverse protection. In this protection scheme of hybrid WDM/TDM PON, each TDM PON with N (normally even) ONUs, is characterized by built-in redundancy, i.e. every two adjacent ONUs form a pair to provide a 1:1 protection.

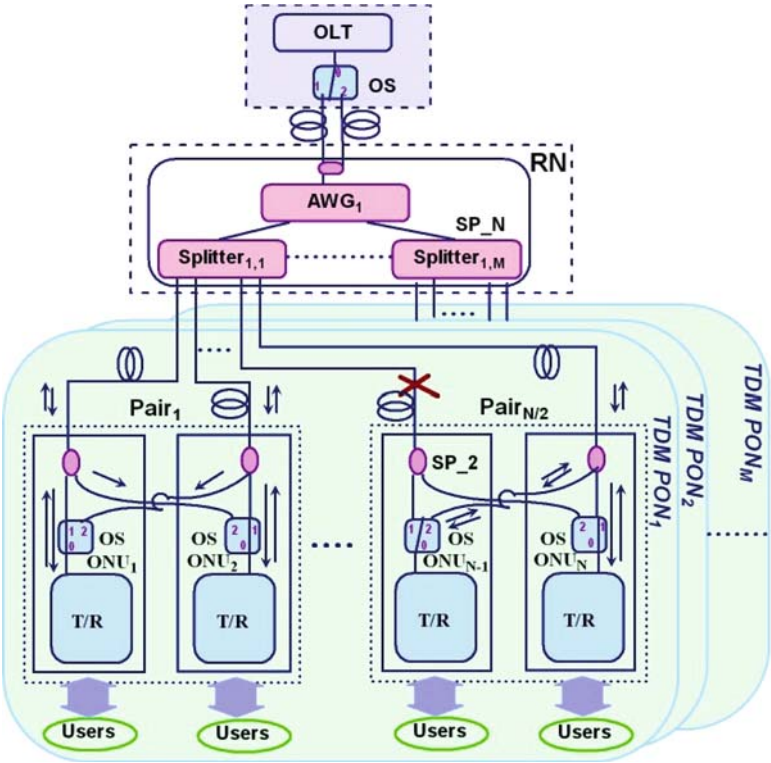

Fig. 5.8 Novel protection schemes for hybrid WDM/TDM PON

Updating from a single TDM PON to a hybrid WDM/TDM PON including his protection scheme is relative simple and cheap since no duplicated components are required. Furthermore, DFs are geographically disjoint since ONUs are situated at different locations.

Similarly to the WDM PON described before, both blue and red bands can be used in our hybrid WDM/TDM PON protection scheme by adding 1×2 splitters and two R/B filters between the one port of the AWG and each $1 \times N$ splitter in the RN. Thus, this hybrid WDM/TDM PON protection scheme also can serve M TDM PONs using $2M$ wavelengths like the previously mentioned WDM PON did.

5.3 Reliability Performance Evaluation

5.3.1 Reliability Requirements and Reliability Data

Requirements for network reliability depend on the market and the considered application. For voice circuits the requirements are not as stringent as for data traffic. With new services being offered where voice and data applications merge

Table 5.1 Equipment reliability data

Equipment	Failure rate (FIT)[a]	MTTR (h)	Asymptotic unavailability
LT	256	4	$U_{LT} = 1.024\ 10^{-6}$
OLT_{CO}	2,500	4	$U_{OLTCO} = 10^{-5}$
ONU	256	24	$U_{ONU} = 6.144\ 10^{-6}$
Fibre cable	570/km	24	$U_{fiber} = 1.37\ 10^{-5}$/km
Splitter (SP)	50 ~ 120	24	$U_{SP} = 0.12 \sim 2.88\ 10^{-6}$
Optical switch	200	24	$U_{SW} = 4.8\ 10^{-6}$
AWG	200	24	$U_{AWG} = 4.8\ 10^{-6}$

[a]1 FIT = 1 failure/10^9 h

(Multi-Protocol Label Switching MPLS, Voice over Internet Protocol VoIP), the distinction between these two types of traffic becomes less clear. No standards exist for network reliability and it is up to the network operators themselves to define to which standards their networks are to be designed.

Some de facto standards exist, though from a market point of view. Some operators offer 5 nines service where the availability is guaranteed to be greater than 99.999%. Verizon's IntelliLight offers 99.9994% availability (99.999% availability corresponds to a connection downtime of no more than 6 min/year). Most operators will offer a suite of services, with different levels of QoS (Quality of Service) or availability.

Time needed to repair a failure is crucial for meeting the connection availability objectives. Equipment vendors may impact on this through designs that are easy to troubleshoot and repair. However, the network operator has primary control of repair times through its maintenance strategy. For calculation purposes and subsequent reporting of downtime estimates to a network operator, established criteria require now the following repair time assumptions: 4 h for central office equipment and 24 h for the outside plant (including fibre cables and remote node) and the ONU.

The input data for our calculations and simulations are shown in Table 5.1. For the reliability figures presented in Table 5.1 we refer to [Chen07], [COST270].

5.3.2 Reliability Models

To estimate connection availability in the considered protection schemes the appropriate availability models need to be derived.

The RBDs related to different recovery architectures are presented in Figs. 5.9–5.14. It has been assumed that the recovery switching after a failure is perfect. We also assume that the power node in a central office has the availability equal to 1, i.e., it does not fail. It is generally true, because there are very robust backups in a central office (diesel engines, etc.).

The series configuration (series system) consists of two or more components (units) connected in series from the reliability point of view. It means that a series system fails if one or more components (units) fail. The parallel configuration

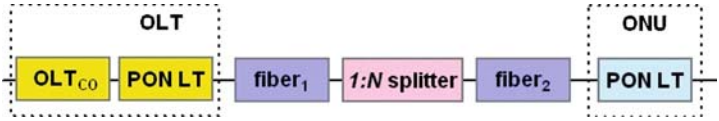

Fig. 5.9 Reliability block diagram for basic architecture

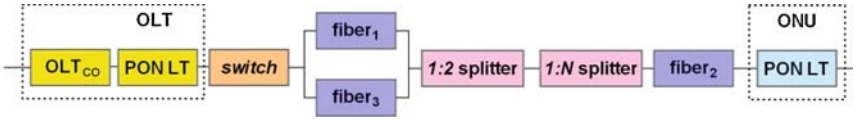

Fig. 5.10 Reliability block diagram for recovery architecture of Type A architecture

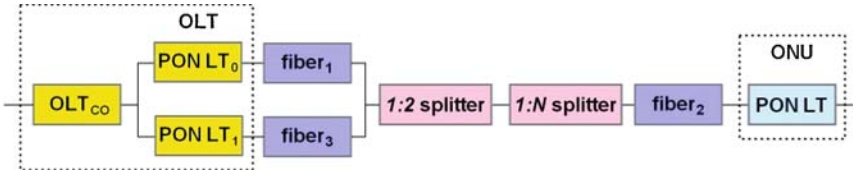

Fig. 5.11 Reliability block diagram for recovery architecture of Type B architecture

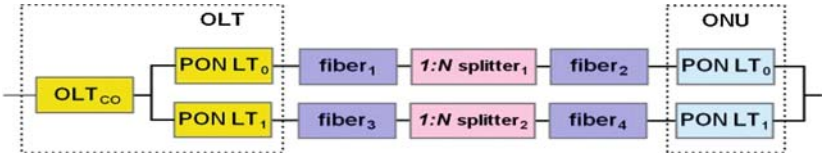

Fig. 5.12 Reliability block diagram for recovery architecture of Type C architecture

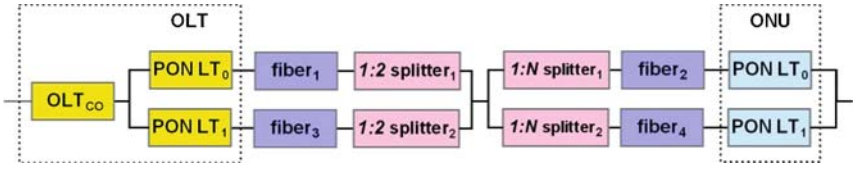

Fig. 5.13 Reliability block diagram for recovery architecture of Type D architecture: full protection

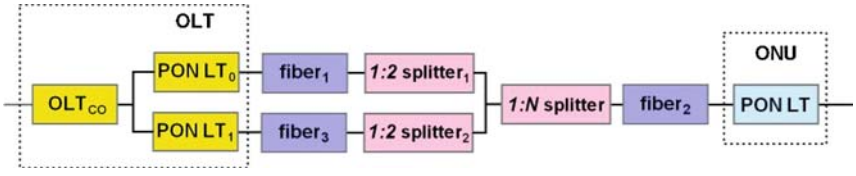

Fig. 5.14 Reliability block diagram for recovery architecture of Type D architecture: partly protected customers

(parallel system) consists of two or more components (units) connected in parallel from the reliability point of view. It means that a parallel system fails if, and only if, all of the components (units) fail.

Equations (5.1)–(5.6) have been derived from RBDs in Figs. 5.9–5.14 according to the definitions of the series and parallel configurations. U_A, U_B, and U_C correspond to asymptotic connection unavailability in Type A, B, and C respectively. U_{D_1} and U_{D_2} represent asymptotic connection unavailability in Type D for customers fully and partly protected respectively.

$$U_{unprotected} = U_{OLT_{CO}} + U_{LT} + U_{FF} + U_{SP} + U_{DF} + U_{ONU} \tag{5.1}$$

$$U_A = U_{OLT_{CO}} + U_{LT} + U_{SW} + U_{FF^2} + U_{SP} + U_{DF} + U_{ONU} \tag{5.2}$$

$$U_B = U_{OLT_{CO}} + (U_{LT} + U_{FF})^2 + U_{SP} + U_{DF} + U_{ONU} \tag{5.3}$$

$$U_C = U_{OLT_{CO}} + (U_{LT} + U_{FF} + U_{SP} + U_{DF} + U_{ONU})^2 \tag{5.4}$$

$$U_{D_1} = U_{OLT_{CO}} + (U_{LT} + U_{FF} + U_{SP})^2 + (U_{SP} + U_{DF} + U_{ONU})^2 \tag{5.5}$$

$$U_{D_2} = U_{OLT_{CO}} + (U_{LT} + U_{FF} + U_{SP})^2 + U_{SP} + U_{DF} + U_{ONU} \tag{5.6}$$

In Eqs. (5.1)–(5.6) the asymptotic unavailability of either equipment or fibre link is indicated by U_i. For description of symbols and their values we refer to Table 5.1. U_{FF} and U_{DF} in Eqs. (5.1)–(5.6) represent unavailability of feeder fibre and distribution fibre respectively. We assumed 10 km long working/protection fibre for FF and 5 km long (in average) working/protection fibre for DF. Thus, $U_{FF} = 10U_{fiber}$ and $U_{DF} = 5U_{fiber}$.

5.3.3 Results

Using the reliability data presented in Table 5.1 and Eqs. (5.1)–(5.6) we calculated asymptotic connection unavailability for each protection scheme. The results are shown in Table 5.2.

Table 5.2 Analytical results for the different architecture types

Schemes	Unavailability	MDT/year (min)
Basic architecture (unprotected)	$2.252\ 10^{-4}$	118.39
Type A	$U_A = 9.339\ 10^{-5}$	49.08
Type B	$U_B = 8.756\ 10^{-5}$	46.02
Type C	$U_C = 1.005\ 10^{-5}$	5.28
Type D Fully protected	$U_{D_1} = 1.003\ 10^{-5}$	5.27
Partly protected	$U_{D_2} = 8.744\ 10^{-5}$	45.96

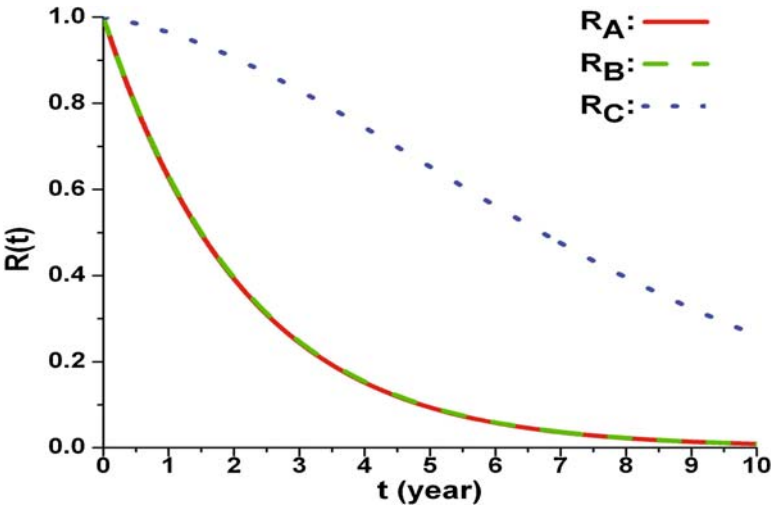

Fig. 5.15 Reliability function for connections in Type A, B and C architectures

It can be seen that providing a limited protection such as in Type A, B and D_2 will decrease connection unavailability compared to the basic architecture. However, the unavailability is still quite high and might not be acceptable for some demanding users. In Type C and D_1 on the other hand, the asymptotic connection availability is close to 99.999% (5 nines) but in these two cases the duplication of all resources is required. Providing this kind of dedicated protection in PON may be very expensive, so novel protection schemes are encouraged in order to achieve minimizing the cost for protection while maintaining an acceptable level of connection availability.

Furthermore, in Table 5.2 the Mean Down Time per year (MDT/year) is shown for each considered scheme. The figures for MDT/year in Table 5.2 represent the mean values calculated over the very long time period. However, service provider needs to define the expected down time that a customer may experience during the contracted period. In the case when no connection interruption occurs during the contracted period the down time will be equal to zero. In contrast, if the failure occurs, the reparation will take a couple of hours or even a couple of days. Therefore, one should take into account the probability that a connection interruption occurs during the contracted period.

In Fig. 5.15 reliability functions for connections in Type A, B, and C architectures are plotted as a function of time. According to the definition given in section 5.1, the reliability function *R(t)* can be seen as a probability of failure-free operation during a specified period of time *(0–t)*. Therefore, the diagrams in Fig. 5.15 are showing the probability that the connection interruption will not occur during the contracted period and thus, one can use this information to calculate the expected mean down time for a customer.

5.3.4 Power Supply

Highly reliable electrical power systems are necessary for all telecommunication elements. Since more optical fibres and electronic components are deployed closer to the home, provision of the primary and secondary backup power sources becomes more and more expensive. To reduce the possibility of single point failures, in a typical network power architecture component redundancy is applied. To achieve that target, most of the central offices should have both battery and diesel back-up to provide energy during loss of AC mains power supply.

Power to the ONU could be provided either from the central office or from centralized locations in the access network. However, a centralized power supply could require the addition of copper media parallel to the fibre for power distribution.

5.4 Conclusions

In this chapter we studied the reliability performance of the PON architectures defined by ITU-T. We compared the connection availability and showed that Type A and B architectures might not be acceptable for critical applications. In these cases it is recommended to either invest in duplicating network resources (Type C) or provide the high available services only to some selected business customers with mission critical service and need of connection availability higher than 5 nines (Type D with full protection). However, the second option can be an economical solution only in the case where majority of the PON subscribers do not need high availability services and are satisfied with an unprotected scheme.

It is obvious that more cost efficient protection schemes that offer the acceptable level of connection availability at low cost per subscriber would be very attractive for both access network providers and subscribers. A further work is needed to study new ideas for protection in access networks in order to propose a feasible solution for the future fibre access network.

Chapter 6
Traffic Studies

Carlos Bock, Jorge M. Finochietto, Gerald Franzl, Fabio Neri, and Josep Prat

This chapter discusses on the incorporation of the Medium Access Control and Quality of Service mechanisms to the optical access network. The high level of sharing of the optical infrastructure compels it and a relevant efficiency in terms of resource usage is expected with the advanced techniques proposed.

6.1 Dynamic Bandwidth Allocation, QoS and Priorization in TDMA PONs

6.1.1 Implementation of a Dynamic Bandwidth Allocation Mechanism

Dynamic Bandwidth Allocation (DBA) is a mechanism for an adaptive sharing of the bandwidth in order to improve the efficiency, the QoS (Quality of Service) and the flexibility of the network. The DBA mechanism aims at managing the network resource by answering at the same time to economical and versatile client-satisfaction constraints. Thus thanks to this enhanced service capability, the DBA mechanism turns out to be of high importance for multi-services TDMA (Time Division Multiple Access) and WDMA (Wavelength Division Multiple Access) networks. Among them, Passive Optical Networks (PONs) may benefit from this mechanism in order to provide a wider range of services (High Definition Television HDTV, Television on Demand TVoD, VoIP, Internet, E1, Plain Old Telephone Service POTS, etc.).

A lot of studies have been carried out on this topic during the recent years. We will first see what is at stake and give an overview of the main kinds of algorithms in the context of the first generations of PON, BPON (Broadband PON, ITU-T G983, International Telecommunication Union), EPON (Ethernet PON) based on the Ethernet 802.3ah (IEEE) (Institute of Electrical and Electronics Engineers) standard and Gigabit Passive Optical Network (GPON, ITU-T G984). Then, simulation results will be presented to highlight the high importance of a severe choice of the DBA algorithm and some important selection criteria will be given.

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6.1.2 Definition and State of Art

DBA mechanism has to answer to the following questions:

- How to detect the ONTs' (Optical Network Terminal) state?
- Which events can trigger an update of the bandwidth allocation between ONTs?
- How to allocate the bandwidth?
- How to allocate/manage the grants?

DBA mechanism is not accurately a single protocol but it gathers message exchange protocols and an algorithm of dynamic bandwidth allocation. The PON standards only specify the main principles of the DBA mechanism in order to allow interoperability between vendors. I.e. deal with the schemes usable to detect the state of the ONTs (for instance "Status reporting" or "Idle cell" mechanisms for BPONs) or the signalisation messages and specific fields used to request or assign bandwidth. The DBA algorithm itself (i.e. the algorithm that selects where to assign which bandwidth) is not standardized.

Lots of works were done on this topic, especially for the EPON access networks, often considered as the more promising and cost effective solution for the next generation of optical broadband access networks than BPON. The youth of GPON might explain the lack of communication and studies on this subject, as normalization work is still in progress.

Dynamic bandwidth allocation algorithms are directly linked to the know-how of the chipset manufacturers and vendors (Passave, Technovus, Motorola/Freescale, Centilium Commmunication, Broadlight, Alcatel, Terawave, ECI, etc.). It is thus quite difficult to find accurate information about what is actually implemented, depending of the vendors and the operators policy. Nevertheless, from the academic side numerous developments have been published for EPON. The algorithms, technically agnostic by themselves, can be generalized to any kind of PON access network with limited adaptations. But their performance strongly depends on considered technology, i.e. the used frame structures and message exchange protocols. We propose a mapping of the main families based on a bibliographical study of EPON DBA algorithms.

DBA algorithms can be classified into two main categories [Garry04], see Fig. 6.1. The first group gathers statistical multiplexing algorithms, and the second one QoS-oriented algorithms. Inside the latter, algorithms can be differentiated according to the kind of the used fair scheduler: a direct (single level) scheduler for a centralized (at the level of the Optical Line Terminal, OLT) control or a hierarchical (multi-level) scheduler for a remote (sharing between OLT and ONTs) control.

The statistical multiplexing group aims at improving the bandwidth use without any service differentiation and so do not support differentiated QoS. The required bandwidth by the ONTs is provided by an adjustment of their transmission window size, based on their instantaneous queue length. The ONTs are considered in whole, there is no differentiation between their traffic flows. The cycle length is neither fixed nor bound, depending on the level of the bandwidth occupancy required by

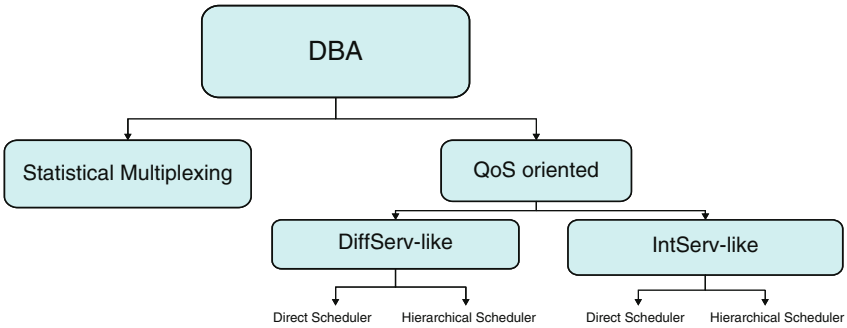

Fig. 6.1 Classification of Dynamic Bandwidth Allocation algorithms

the ONTs only. In [Kramer02cm], the ONTs are pooled individually by the OLT, and transmission windows are granted in a round-robin fashion. Wei [Wei05] proposes a quite similar algorithm with a fast response of the OLT granting scheme. Byun [Byun03] adds an estimated state of the ONTs' queue described analytically in order to better estimate the proper allocation of bandwidth in case of bursty traffic flows. The main drawback of the statistical multiplexing approach is unfairness, i.e. the risk of having the bandwidth monopolized by heavy loaded ONTs. One solution is to use bounded windows [Kramer02cm].

The second family, QoS-oriented resource allocation, takes care of QoS and differentiation of services, through QoS aware bandwidth reservation and/or prioritization mechanisms. An ONT can have one or several queues, for each traffic source or group of traffic sources (e.g. traffic classes). "DiffServ-like" algorithms are based on a prioritization mechanism of the queues in order to differentiate the ONTs' services in sense of the IETF (Internet Engineering Task Force) differentiated services (DiffServ) IP QoS. Three levels of priority are defined corresponding to the EF (Expedited Forwarding), AF (Assured Forwarding) and BE (Best Effort) levels of DiffServ. Higher traffic classes are provided with a better QoS relative to the lower priority classes. QoS is provided only in a qualitative way, i.e. higher priorized flows get better QoS than lower priorized flows, but dedicated QoS levels can not be granted. Otherwise they are said "IntServ-like", considering only two kinds of queue, a guaranteed and a best effort one. These rely on bandwidth reservation and admission control mechanisms in order to provide lossless services with deterministic delay bounds. QoS is provided in a quantitative way, in sense of the IntServ IP QoS.

Choi [Choi02] presents a DiffServ-like algorithm implemented by a direct scheduler. The bandwidth is shared by the OLT between the different classes and in the order of their priority level. The cycle length is bounded. Luo [Luo05icc], [Luo05oc] allow to limit the bandwidth allocated to ONTs at their SLA level and implement an extra class-based traffic prediction reducing the frame delay and the frame loss figures, leading to improved performance in case of multi-ONTs and multi-services networks. In [Assi03], the scheduler is hierarchical, based on the

re-use of the bandwidth left by the heavy loaded ONTs by the light loaded ONTs. Kramer [Kramer02jon] and Ghani [Ghani04] present close algorithms. The first one is based on a statistical multiplexing at the OLT level, resulting in variable cycle length. The latter relays on a modified start time fair queuing based scheduler inside the ONTs instead of a strict priority scheme.

Examples of IntServ-like and direct scheduler based DBA algorithms are given by Ma [Ma03], Chen [Chen03] and Zhang [Zhang05]. Ma [Ma03] is a guaranteed bandwidth protocol, with a fixed cycle length and the re-use by the "best effort ONTs" of the bandwidth left by the light loaded "guaranteed bandwidth ONTs". Chen [Chen03] uses a more efficient fair sharing of the excess bandwidth between the ONTs according to their granted bandwidth but leads to a variable cycle time (i.e. extra jitter). Zhang [Zhang05] proposes an adaptive MAC (Medium Access Control) polling protocol based on the Earliest Packet First algorithm, scheduling the transmission of the different ONTs in an ascending order of the arrival time of the first packet waiting in the queue of each ONT. Kim [Kim05] aims at managing the "remnant time" for each ONT in order to bind the effect of bandwidth shrinkage. Zhang [Zhang03] uses a hierarchical scheduler based on a deterministic effective bandwidth admission control and resource allocation mechanisms and a generalized processor sharing scheduler.

Thus DBA aims at not only using bandwidth efficiently, by an adaptation to the bandwidth fluctuations making possible to increase the number of connected users, but also controlling the QoS at the access network level. This is of major importance in the access network where these first miles contribute largely to the end-to-end user QoS. So a special focus must be made on the impact on the QoS in the scenario of migration of a non-DBA system (i.e. fixed assigned bandwidth) to a DBA one.

6.1.3 Migration Toward a Dynamic Bandwidth Allocated BPON and Selection Criteria

If utilisation improvements are intended the implementation of a DBA mechanism might be applicable, however, be aware that DBA can lead to worsening of the QoS compared to a static configuration. In the following we present simulations results highlighting the impact of a simple, i.e. non specifically optimized, DBA mechanism on several traffic flow profiles.

A BPON access network of 11 ONTs for business customer has been run under the OPNET© simulation software [Niger02]. The PON capacity is 155 Mbps down and upstream. Each ONT offers one voice service (E1-Circuit Emulation voice) and one data service. Voice services are modelled by an ATM (Asynchronous Transfer Mode) CBR-like (Constant Bit Rate) connection. Guaranteed data services are modelled by an ATM CBR-like connection and more bursty data services by an ATM VBR-like (Variable Bit Rate) connection. Each ONT is linked to a single user and the generated flow of traffic is equally shared between the guaranteed and bursty services. Table 6.1 summarizes the kinds of simulated services and corresponding bit rates.

Table 6.1 Definition of service sets for business customers

Types of service	Mbps
Voice E1 CE service	1
Guaranteed data service	
Guaranteed bit rate	10
Bursty data service	
Guaranteed bit rate	2, 4 or 20
Peak bit rate	34 or 155

Simulations were made in static and in DBA mode. In static mode, a fixed bandwidth is assigned by the OLT to each ONT. An internal scheduler inside each ONT shares the bandwidth between the several supported services according to their priority levels. Voice service is given a strict high priority. The traffic of the bursty data services is shaped inside the ONTs, stored in a buffer at the customer bit rate interface (34 or 155 Mbps) and read at the guaranteed bit rate of the service (2, 4 or 20 Mbps). In dynamic mode, an IntServ-like algorithm based on a direct scheduling by the OLT is used, close to [Chen03]. The algorithm is kept simple, without any optimization taking into account the service set. The cycle time is fixed. Voice services are assigned with fixed bandwidth (1 Mbps), so are outside the scope of the DBA. Once the bandwidth allocated to the several voice services, the dynamical bandwidth allocation mechanism between data services can really take place. The bandwidth left by the lightly loaded ONTs (using less than the sum of the guaranteed bandwidth of their supported data services) is allocated to the heavily loaded ONTs to transmit the bursty data services. The transfer delay for each service was calculated.

The main outcomes of this migration scenario towards a DBA system are:

- A slight increase of the transfer delay for the voice service: in static mode the bandwidth is allocated once and for all to the ONTs according to the guaranteed bit rates of the subscribed voice and data services. Because of the strict priority mechanism implemented with the higher level of priority for the voice service, if necessary this service can enjoy more bandwidth than its guaranteed one (1 Mbps) by using the bandwidth dedicated to the data services. In the implemented DBA mechanism, a fixed bandwidth is dedicated to the voice service, set to its guaranteed bandwidth level (1 Mbps). Thus the voice service can only use this fixed bandwidth. So in average the transfer delay is higher.
- Impact of the DBA time parameters on the QoS of the guaranteed data service. The transfer delay of this service increases with the DBA mechanism due to its reaction time. This is due to the fact the transfer delay of the queue length message sent from the ONT to the OLT is much important than the ONT source traffic time. This gap led to a no more actual information transmit to the OLT and thus to deferred cells until the next allocation cycle. One solution may be the use of a predictive method of traffic to better estimate the needed bandwidth.
- On the contrary DBA mechanism largely improves the bursty data service (with a strong elastic traffic profile). In DBA mode, more than the guaranteed bit rate

Table 6.2 Transfer delay (in ms) of bursty data services with different guaranteed bit rates versus customer's activity rate, in static and Dynamic Bandwidth Allocation modes

	Static mode	DBA mode		
Customer's activity rate	100%	100%	50%	25%
2 Mbp/s	750	120[a]	70	50
4 Mbp/s	370	160	40	26
20 Mbp/s	65	50	37	26

[a] Simulation artefact

can be allocated to the bursty data service. The excess traffic of this service, beyond its guaranteed bit rate, is considered as best effort traffic, which can be transmitted depending of the load of the other ONTs. Thus an ONT can have the possibility to transmit limited size burst over the PON at the customer interface bit rate. Transfer delays of bursty data services with different guaranteed bit rates in static and DBA modes are listed in the Table 6.2.

Regardless the kind of PON technology those first results showed that DBA mechanism improves the transfer delay of bursty traffics, but things are not so settled for CBR-like traffic. Thus the DBA algorithm must be chosen considering the service set to be provided and the QoS essential to fulfil all existing SLAs.

More generally, DBA algorithm should be chosen depending on the services set in terms of

- Impact on QoS of existing and intended new services
- Compatibility of the DBA time characteristics with temporal behaviour of services
- Ratio between the implementation complexity of the algorithm and the potential for improved performance

From an integrated operator point of view, selection criteria could be the following. DBA algorithms need to be

- Scalable, i.e. able to follow the evolution of the network and its services
- QoS oriented to assure existing and intended future SLAs
- Fair in the redistribution of the excess bandwidth available
- Robust and isolated towards misbehaving users or applications [Kramer05]

They thus should be chosen taking into account

- The kinds of provided services, i.e. their profiles (temporal distribution)
- The management policy for the provided services (prioritization of the services, of the users, etc.)
- Their compatibility with the higher level protocols (interaction with Transmission Control Protocol TCP, etc.)

Expected improved performance needs to be balanced with the complexity degree of the algorithm, linked with the cost for mature network management staff.

6.2 WDMA/TDMA Medium Access Control

Given the huge aggregated bandwidth fibres commonly provide with WDM technology we need to acknowledge that with TDM alone we can by far not exploit the capacity available. Thus, there is a strong need to develop novel high-speed architectures and protocols for combined WDM/TDM MAC.

In [Bengi02b] different basic and novel MAC protocols for WDM-based LANs/MANs (Metropolitan Area Networks) are proposed and analysed. Solutions for direct support of distinct QoS classes over the WDM transmission layer are provided for a group of single hop networks, and highly dynamic reservation-based access protocols for passive-star and ring topology presented. Note that the performance studies presented are not performed explicitly for access networks, i.e. we assume traffic between any two nodes connected via the PON as typically found when considering peer services across metropolitan area networks as shown in Fig. 2.20 where every Optical Network Unit (ONU) on the left can transmit timeslots (Ts) to any ONU on the right by simply changing the wavelength and timeslot. The core routing element is the arrayed waveguide grating (AWG) which performs the wavelength switching of the multiplexed timeslots.

6.2.1 Access Protocol for Arrayed Waveguide Grating Based TDMA/WDMA PONs for Metropolitan Area Networks

A simple scheduling algorithm represents a TDMA-based all-to-all medium access scheme which provides guaranteed capacity for each source-destination pair. The network nodes are allowed to share the available bandwidth equally and fairly. Due to the inherent rate limiting mechanism adopted in this scheme a throttling of the nodes' offered traffic load is achieved avoiding occasional or complete starvation. Such algorithms are proved to be optimal concerning the frame length, and are also scalable to different network sizes.

For AWG based PONs such a scheduling scheme can directly be derived from the properties of the AWG, which in [Bengi02b] is called AWGM (arrayed waveguide grating multiplexing). Concerning the performance of such AWGM PON, it can be demonstrated that a parallel transmission buffer configuration allows for a much more efficient use of one frame. Under this strategy, each destination node is assigned a separate transmission buffer where the corresponding packets are stored independently as shown in Fig. 6.2.

Parallel buffering avoids the impact of the head-of-line blocking problem leading to a substantial deterioration of the queuing delays compared to single transmission buffer concept. In case the different transmission buffers are supplied equally with a Poisson arrival process, the mean packet queuing delay $E[d_q]$ may be determined analytically by using a modified M/D/1 model adapted to TDMA schemes. Accordingly, the packet delay consists of three terms, the transmission time of a

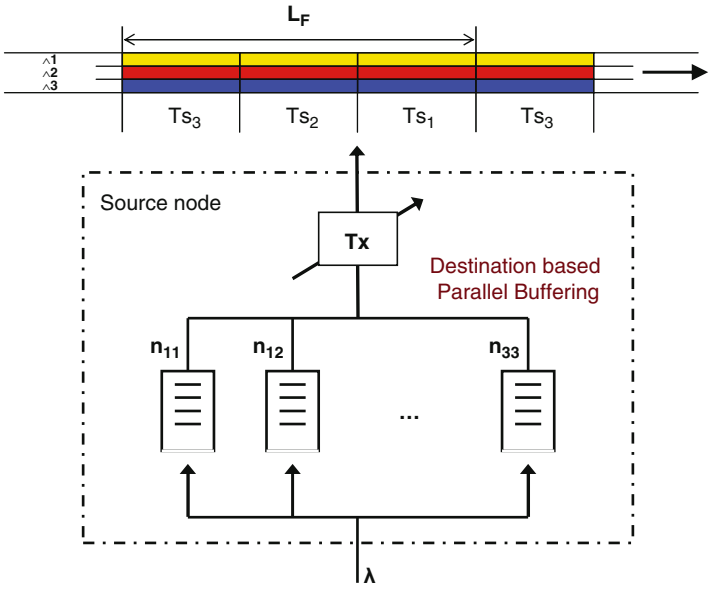

Fig. 6.2 Destination based parallel buffering at source nodes

packet, the frame synchronisation period and the waiting time E[W] associated with a M/D/1 queuing model, i.e. $E[W] = \rho(1/\mu)/[2(1-\rho)]$ with $1/\mu$ being the mean service time. Each transmission queue (corresponding to a certain destination node) can be modelled by such a queuing system, thus, by setting $1/\mu = L_F$, the mean packet queuing delay can be written in the following form (normalised to slots):

$$E\left[d_q\right] = 1 + \frac{L_F}{2} + \frac{\rho L_F}{2(1-\rho)} \tag{6.1}$$

where L_F denotes the frame length of the scheduling scheme and ρ represents the utilisation of the underlying queuing system, i.e. the utilisation related to a specific source/destination pair. When further $S_{(s,d)max}$ denotes the maximum achievable throughput belonging to a certain source/destination pair, ρ can be given as $S_{(s,d)max}/S_{max}$ with S_{max} specifying the obtainable network throughput. By substituting $L_F = \max\{M, n^2\}$ and $S_{max} = \min\{M, N^2\}$, we directly obtain the maximum (worst case) mean queuing delay $E[d_q]$ with respect to the achievable network throughput S_{max}.

The performance comparison in terms of the two different transmission buffer configurations can be seen in Fig. 6.3, where the mean queuing delay and throughput for single and parallel buffering are plotted versus the offered load per node in packets per slot for $M = n \times N = 50$ nodes with $n = 5$ and a fixed (deterministic) data packet length of one slot, i.e. $L = 1$. Note that the analytical results obtained show excellent agreement with the simulation results in the parallel buffers case.

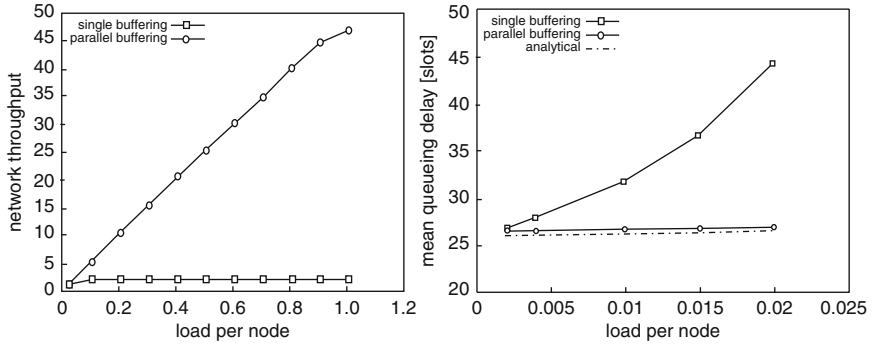

Fig. 6.3 Performance of buffering concepts for arrayed waveguide multiplexing single hop network

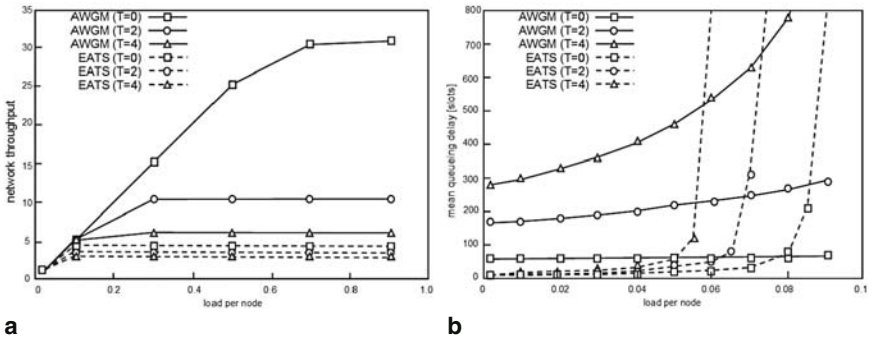

Fig. 6.4 (a) Throughput and (b) queuing delay for arrayed waveguide multiplexing and earliest arrival time scheduling MAC protocol

The degradation of the queuing delay significantly increases for higher loads, while for network loads higher than one packet per slot (load per node exceeding 0.02 packets per slot) the deterioration appears to be severe. For network loads beyond one packet/slot shown in Fig. 6.4, the throughput of the parallel buffering case increases linearly until reaching the maximum throughput for M = 50, whereas the single buffer case leads to a constant throughput of about 2 in the heavily loaded region. The parameter T analysed in Fig. 6.4 represents the tuning time required for tuning the transmitters and receivers prior to sending respectively receiving a packet. Increasing T decreases the throughput and increases the queuing delay, as can be seen in Fig. 6.4.

We see that the throughput of an AWG-based PON (Fig. 6.4) using AWGM access is much larger than that of a passive stat coupler based PON (Fig. 6.5) using the Earliest Arrival Time Scheduling (EATS) protocol for equal number of ONUs. EATS relies on a TDMA scheme to access the control channel for wavelength and time-slot reservations – thus prior to transmission a full reservation cycle is

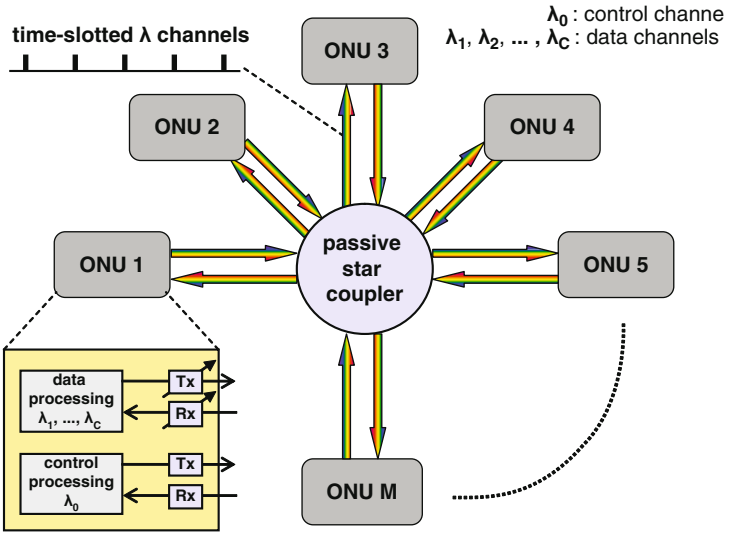

Fig. 6.5 Passive star coupler based WDM PON architecture

performed and both, a timeslot and the receiver need to be idle, to grant a positive acknowledge for packet transmission.

The results depicted in Fig. 6.4 show that the flexibility of a reservation-based access protocol (EATS) leads to much more beneficial access delays for low load regions, whereas the use of a fixed TDMA access scheme (AWGM) offers a significantly slighter increase of delays for overloaded conditions.
The basic features of the considered AWG based single hop system are

- Non-blocking device
- $N^2 \times N^2$ maximum connectivity
- Commercially available

while the presented AWGM access control is characterised by

- Simplicity (can be easily realised in hardware)
- Requires parallel queuing at the source nodes
- Provides satisfactory throughput results particularly for medium network loads

It is obvious that due to the static channel assignment of the AWGM access scheme the bandwidth utilisation of the nodes is not adaptive to the current traffic conditions, i.e. although the AWGM-PON inherently outperforms the passive-star PON in terms of bandwidth utilisation, the static nature of the considered MAC protocol may lead to large degradations of the packet delay, especially for variable-length messages. Finally, note that the impact of fractal traffic on the corresponding system performance is disregarded here since TDMA-based access schemes behave typically not critical to dynamic (bursty) traffic patterns.

6.2.2 Geographical Bandwidth Allocation

If we consider the physical distribution of customers in a geographical area, and the possible different bandwidth needs depending on the hours in a day/week for example, another type of traffic routing algorithm can be proposed for improved bandwidth usage efficiency.

Being the tuneable lasers a key cost critical component and as laser sharing factor is an important parameter to evaluate the network performance, utilization of the lasers needs to be optimized.

Geographic Bandwidth Allocation (GBA) [Bock05] allows an efficient use of optical devices by offering bandwidth on demand to different locations. With the routing properties of an N × N AWG located at the OLT and tuneable laser sources, the network can assign bandwidth on demand to each of the output ports of the OLT's AWG, allowing bandwidth allocation depending on traffic patterns and instantaneous network utilization on different geographic locations.

Each laser serves a limited number of sub networks which are spatially separated and cover different kind of users and services. The laser is time-shared and transmission is performed by tuning the specific wavelength to reach the network sub segment and sending the data burst. To maximize network throughput, a data traffic pattern dependent balance, needs to be struck between data burst length and laser tuning time. These two parameters affect network latency and throughput. Calculations show that to achieve throughput levels higher than 0.9, tuning times should be in the range of hundreds of nanoseconds and bursts lengths greater than 100 kbits considering data rates of 2.5 Gbps or greater. This can be seen in Fig. 6.6b with a simulation using 16 lasers at 2.5 Gbps considering a saturated scenario.

As an example, application of GBA would allow the network to concentrate bandwidth during the mornings and early afternoons in business and commercial areas and during evenings in residential areas, maximizing the utilization of the network resources.

For the AWGM-PON, every fibre connected to the AWG transports the same capacity all the time. However, it does not require active wavelength switching/

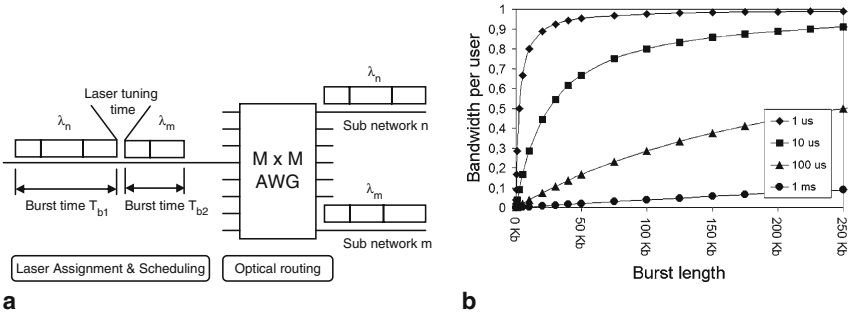

Fig. 6.6 (a) Geographic bandwidth allocation burst assembling and (b) bandwidth per user vs. burst length for different tuning times, at 2.5 Gbps

filtering – all this is done passively by the AWG. Within a group sharing, the assignment of timeslots to ONUs might be adaptive, given the ONUs can access more than one stream of timeslots simultaneously – i.e. can receive parallel channels as done with GPRS.
Some potential applications:

- MAN: to interconnect access networks to support peer services.
- FTTC: assume you place all the tuneable receivers in the curb and transport the detected timeslots to ONUs over copper.
- Video On Demand with guaranteed bandwidth 24 h a day.

6.3 Access Protocols for WDM Rings with QoS Support

We focus now again on time-slotted WDM ring networks due to their common application. In order to avoid collisions on the individual wavelength channels of time-slotted WDM networks, MAC protocols are necessary to arbitrate channel access. Several access protocols for all-optical slotted WDM rings have been proposed [Kang95], [Marsan96], [Fransson98], [Fumagalli98], [Kamal99]. Most of them are based on the assumption that as many wavelength channels are available as there are nodes in the network; which results in a serious scalability problem. Moreover, some proposals require transmitter and/or receiver arrays at each node [Kang95], [Fumagalli98] associated with high equipment costs.

Bengi [Bengi02b] introduces a medium access protocol applying distributed control supporting real-time as well as data services in slotted multi-hop WDM ring networks (Fig. 6.7). The presented QoS mechanism establishes connection-oriented as well as connection-less transmission. The photonic packet switching device in its network interface unit (NIU) consists of a header processor, a fibre delay line, an optical switch, a switch control block, semiconductor optical amplifiers (SOAs), and so on. The functional relevant are depicted in the NIU sketch shown in Fig. 6.7b; note that switch and scheduler control blocks were integrated in a general NIU control block as these are interdependent. The switch control logic sets the optical cross connect (OXC) to (A) drop a packet to the node's receiver (Rx) or to let the amplified slot propagate through the node (optical bypassing) and (B) insert a packet from the transmitter onto the ring when an empty slot has been detected or a full slot is destined to the node, i.e. is dropped, and thus can be reused. Obviously, a WDM de-multiplexer (AWG) and multiplexer (star coupler) are included in the NIU in order to handle all incoming slots separately and simultaneously. On the electrical side the node may have C independent transmission buffers allowing it to transmit data packets on any wavelength whenever an idle slot has been detected and a packet currently is waiting for transmission on that particular wavelength (parallel buffering configuration).

The studied MAC protocols are based on the Slotted Ring mechanism [Hopper88], [Adams94], in which equally-sized slots circulate on the ring and can

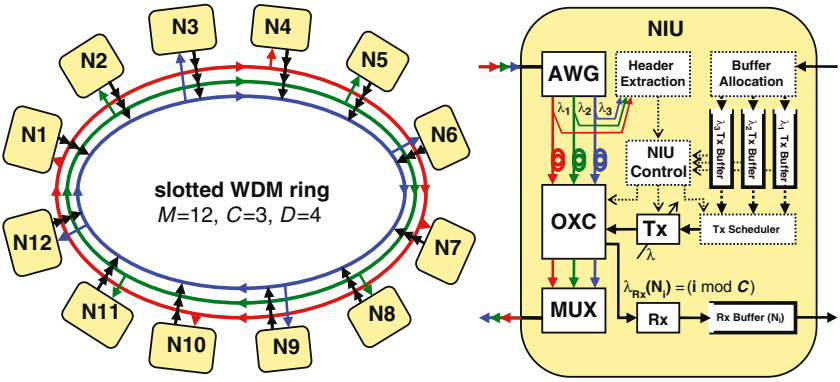

Fig. 6.7 Multi-hop WDM ring network (12 nodes, 3 wavelengths)

be immediately used by any source node for data transmission when a slot is empty. Release of packets at destination nodes allows for an efficient reuse of slots along the ring.

6.3.1 Analytical Model

The ring network consists of M nodes equally spaced around the WDM ring accommodating C wavelengths. Each node generates fixed-length (t_s) packets following a Poisson distribution with the mean arrival rate λ, yielding an overall network load of $\Lambda = M \cdot \lambda$; packet-destinations are uniformly distributed, i.e. a uniform traffic scenario is also assumed. Slot reuse is performed immediately, i.e., in the current slot of the packet just dropped. In that case the mean packet access delay, $E[da]$, which is defined as the time elapsing between the instant where a packet arrives at the head of the transmission queue and the transmission of this packet can than be calculated as

$$E[d_a] = \frac{t_s}{2} + t_s \frac{\Lambda \cdot t_s \cdot M - 2C^2}{2CM - \Lambda \cdot t_s \cdot M + 2C^2} \tag{6.2}$$

6.3.2 Numerical Results

For numerical performance study a 10 km ring accommodating four or eight wavelength-channels, each operating at 2.5 Gbps, is used. Since the maximum achievable throughput of a single (one-channel) slotted ring for the uniform traffic scenario equals two times the medium capacity – slot reuse case – the total network capacity

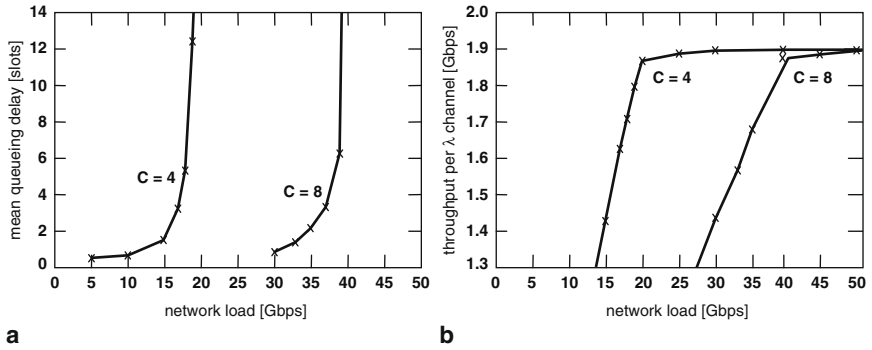

Fig. 6.8 (a) Mean queuing delay and (b) network throughput ($M = 80$)

efficiently equals 20 respectively 40 Gbps. Figure 6.8 clearly depicts these system limits via (a) exponential rise of mean queuing delay, and (b) saturation of channel throughput.

The so far considered simple access strategy represents an extension of the basic Slotted Ring mechanism to multi wavelength environments. Intrinsically it is suited to accommodation of best-effort traffic only, i.e. does not support differentiation among packets in order to achieve differentiated QoS.

6.3.3 Access Protocol Supporting QoS Differentiated Services

Since one wavelength channel is shared by several destination nodes, a multi-hop WDM ring is considered as the underlying network architecture. The channels are divided into several slots allowing data packets to be transmitted and received in a highly bandwidth-efficient way. According to the considered architecture, it is assume that each node is equipped with one tuneable transmitter and one fixed receiver. The so-called a-posteriori access strategy, where the corresponding data packet is selected from the appropriate transmission buffer after having detected the signalling information, is used. The QoS control scheme adopts a frame-based slot reservation strategy including connection set-up and termination, which only marginally increases the signalling and node processing overhead. Thus, a hybrid protocol that combines connection-oriented and connection-less packet transmissions is obtained.

6.3.3.1 Network Architecture

The considered system is based on a ring topology interconnecting M nodes via a single unidirectional optical fibre, as shown in Fig. 6.7. The optical bandwidth of

the fibre is divided into C wavelength channels λ_i, which in turn are divided into fixed-length time slots that exactly offer the space required for one data packet. Slots circulate on the ring and can be empty or full according to the Slotted Ring scheme. It is further assumed that the slots are perfectly synchronized between the optical channels and that the C wavelengths are assigned in a cyclic (interleaved) fashion to the M destination nodes. Consequently the slotted channels serve disjoint subsets of destination nodes, i.e. $D = M/C$ nodes have to share one drop channel. Since slot reuse is assumed, the slots of a channel may be filled and released several times within one ring latency, yielding improved statistical multiplexing and thus efficient resource utilisation.

To alleviate the potential head of line (HOL) blocking, one separate queue is assigned to each optical channel available in the network, causing a total of C access-buffers at every source node. The allocation of data packets to the C buffers is determined according to $c = i \bmod C$, with i being Node index.

6.3.3.2 Access Control

On arrival of a slot, the node has to determine if the slot is empty or not. Only if a slot is found empty it can be used to transmit a buffered packet (a-posteriori packet selection strategy). Consequently neither channel- nor receiver-collision, i.e. no packet losses, can occur. However, if more than one optical channel is carrying an empty slot at the same time some buffer selection rule needs to be applied since only one packet may be transmitted per slot time due to the single tuneable transmitter assumption. Studied Buffer Selection Strategies are: Random (RND), Longest Queue (LQ), Round Robin (RR), Maximum Hop (MH), and C-TDMA, a scheme typically used in circuit switched TDMA systems.

6.3.3.3 QoS Support

To guarantee QoS requirements, a strong control on packet delays and node throughputs is in general required. In accordance with the ATM concept [ATM-Forum95], several QoS classes such as CBR, and VBR traffic classified as real-time services, and ABR (Available Bit Rate), and UBR (Unspecified Bit Rate) traffic related to data services, can be distinguished. For simplicity only real-time and data services are separately studied. To handle them individually it is necessary to split the buffering to the different classes. Note that not necessarily individual buffers are required if selective picking of buffer-cells is supported.

For real-time services, a connection-oriented protocol comprising connection set-up and release is proposed. CBR (isochronous) and VBR (asynchronous) real-time services are thus accommodated by reservation of equidistantly spaced slots on the ring to ensure constant delay between successive CBR/VBR packets during sessions.

To enable connection-oriented packet transmissions it is necessary to subdivide the ring into so-called connection frames with the frame size equal to D = M/C.

Slot indices within these frames are uniquely assigned to destination nodes reachable on a channel. Each node maintains a connection table for keeping track of the currently existing (or being established) connections on the ring. Note that the periodical access to the reserved slots comprising a connection is occasionally interrupted by in-transit packets, since in-transit packets are given higher priority over local traffic due to the lack of flexible optical buffering options.

For data services differentiation among ABR and UBR traffic is necessary. ABR service requirements can be met by reserving slots according to the stated minimum bit rate from the available slots given by the node's connection table, handling access packets like UBR or best-effort services, which simply uses a slot for packet transmission whenever it is found unreserved and empty. Thus in fact two scheduling schemes are sufficient to support all four QoS classes common from ATM.

6.3.3.4 Fairness Control

When networks are operated under heavy load, fairness problems are likely to arise in multi-hop networks, particularly for non-uniform traffic scenarios. Throughput and delay fairness is an intrinsic necessity for QoS service provisioning, thus fair allocation of the available network resources to individual flows must be assured, i.e. HOL blocking among nodes avoided. Bengi [Bengi01] adopt an extension of the ATMR (ATM Ring) global fairness protocol [Imai94] to the multiple channels case, referred to as M-ATMR. The M-ATMR protocol represents a credit allocation scheme and provides fairness control by means of a distributed credit mechanism with cyclic reset scheme based on monitoring. Note that the M-ATMR fairness control scheme is only applied to the data traffic transmissions, i.e., for the unreserved bandwidth in the network.

6.3.4 Performance Study

6.3.4.1 Performance Analysis for Best-Effort Transmissions

The objective of the used semi-Markov model is to determine the channel throughputs and the mean queuing delays of the considered access protocol. Several model assumptions need to be settled: (a) network nodes operate equally and independently, (b) system time is normalized to slots, (c) packets have fixed lengths, (d) node generates data packets according to a Poisson process with mean arrival rate λ, (e) every node may generate in maximum one data packet per slot, (f) destination addresses of the generated data packets are uniformly distributed among all other network nodes, (g) queue size B is finite and identical for all nodes.

Given the assumptions global states and an according state diagram can be derived. The possible states a packet generating node (traffic source) can reside are: idle = currently no data packet is waiting for transmission, synchronising = waiting

for the next slot header while a data packet is waiting for transmission, evaluating = detecting and evaluating a slot header (processing time), waiting = wait for the next slot (current is occupied), transmitting = putting a data packet on an empty slot.

The mean values for these states at boundary traffic load ($\lambda = 1$) are: Sojourn time of idle state equals one slot, i.e. $t_{idle} = 1$. For synchronisation a source node has to wait in average half a slot duration, i.e. $t_{sync} = ½$. For evaluation a deterministic duration is required, i.e. $t_{eval} = T_p$ (processing time), for simplicity reasons set $T_p = 1$. The waiting time till the next slot (if the current is found occupied) is exactly one slot time, i.e. $t_{wait} = 1$ and finally the transmission state has constant timing also, i.e. $t_{tx} = 1$, as exactly one data packet may be transmitted at each slot time (if a corresponding empty slot was available). Note that nonzero transmitter tuning times are not taken into account since it would only introduce a constant delay overhead for transmission (a time-offset) not affecting the operation of the considered access schemes.

Tables 6.3 and 6.4 depict the impact of the number of concurring nodes and wavelength channels on the protocol performance. It can be clearly seen that an increase in the channel number leads to substantial performance gains while performance degradation due to higher node/channel ratio is less significant. This reveals that many nodes can be supported without severely degrading the overall performance of the considered access scheme. Figure 6.9 relates delay and throughput for the case of a ring with 16 nodes and 4 wavelengths (i.e. $D = 4$). The small differences encountered for different strategies lets us stress that the RND scheme is a satisfactory trade-off between implementation complexity (costs) and performance, particularly for the typically non-heavy loads encountered in most operational networks.

Table 6.3 Best-Effort performance (4 wavelengths, $\lambda_i = 0.009$)

	$D = 3$		$D = 4$		$D = 5$		$D = 6$		$D = 7$		$D = 8$	
$C = 4$	Thr.	Delay	Thr.	Delay	Thr.	Delay	Thr.	Delay	Thr.	Delay	Thr.	Delay
RND	2.71	88	3.57	141	4.52	269	5.39	931	5.92	6,738	6.03	14,505
LQ	2.71	95	3.60	154	4.52	279	5.36	772	6.03	6,202	6.15	12,611
RR	2.68	86	3.59	143	4.47	263	5.35	768	5.95	7,050	6.10	13,396
MH	2.70	89	3.61	150	4.43	277	5.35	870	5.91	7,312	6.04	15,046
C-TDMA	2.71	89	3.59	144	4.46	268	5.36	807	5.97	6,027	6.08	13,998

Table 6.4 Best-Effort performance (8 wavelengths, $\lambda_i = 0.018$)

	$D = 3$		$D = 4$		$D = 5$		$D = 6$		$D = 7$		$D = 8$	
$C = 8$	Thr.	Delay	Thr.	Delay	Thr.	Delay	Thr.	Delay	Thr.	Delay	Thr.	Delay
RND	10.5	1,564	11.8	6,836	12.7	9,384	13.1	12,734	13.4	16,197	13.4	18,819
LQ	10.6	970	12.2	6,112	12.9	9,649	13.2	12,113	13.5	15,529	13.7	17,199
RR	10.6	1,604	11.9	6,456	12.7	9,852	13.1	12,582	13.3	15,851	13.5	17,576
MH	10.4	2,190	11.7	6,771	12.6	9,814	13.1	12,642	13.3	15,529	13.5	19,004
C-TDMA	10.6	1,039	12.2	5,977	12.8	9,865	13.2	12,255	13.4	14,985	13.7	17,676

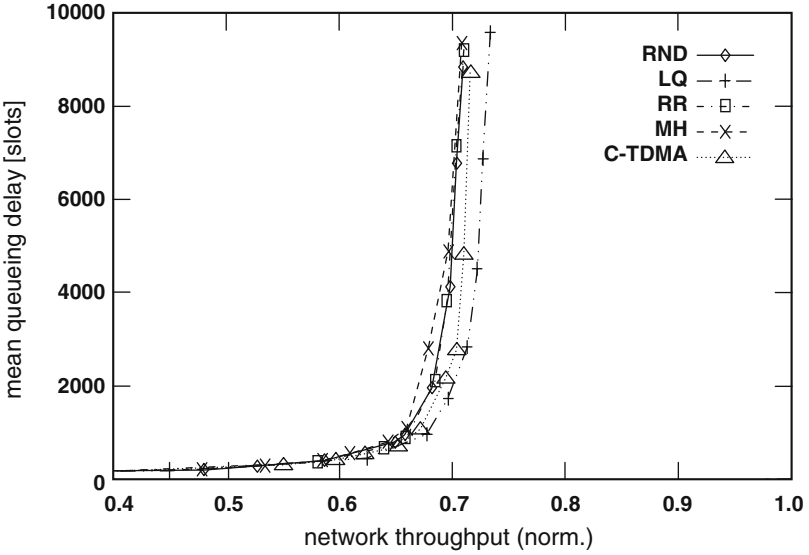

Fig. 6.9 Queuing delay for different selection strategies ($M = 16$, $C = 4$)

6.3.4.2 Real-Time and Data Traffic Performance

For simplicity data traffic with QoS, i.e., ABR traffic is not considered here. IP packet's variable lengths are also not considered, i.e., assume that they get mapped to equally sized units that perfectly fit into slots.

Some further assumptions:

- Packets belonging to real-time sessions are handled in a node by a dedicated real-time buffer, while data packets get queued in a separate data buffer.
- Arrival rate of the Poisson distributed real-time traffic $\lambda_r = r \cdot \lambda$, where r indicates the percentage of real-time traffic.
- Mean length of the real-time session units $L_r = 25$, the mean packet length of data traffic packets $L_d = 10$ slots.

The metric for real-time traffic performance is the connection set-up delay as transport delay in our architecture (transport via circuit switched capacity shares) is a distance dependent constant. The connection set-up delay is defined as the time elapsing between arrival of session request and completion of connection set-up.

Figure 6.10 illustrates connection set-up delay versus network throughput for D = 4, r = 30% real-time traffic and different ring lengths expressed by the total number of slots circulating on the ring, i.e. $n_s = 100$, 200, and 400. For 2.5 Gbps channel bit rate and 1,000 bits slot size, the physical ring lengths are 8, 16, 32 km, respectively.

Note that the connection set-up time for the largest considered ring size ($n_s = 400$) is about 3,600 slots, i.e. ≈1,440 µs only and the delays are nearly constant in respect to total traffic load, i.e. scalable in terms of current traffic load.

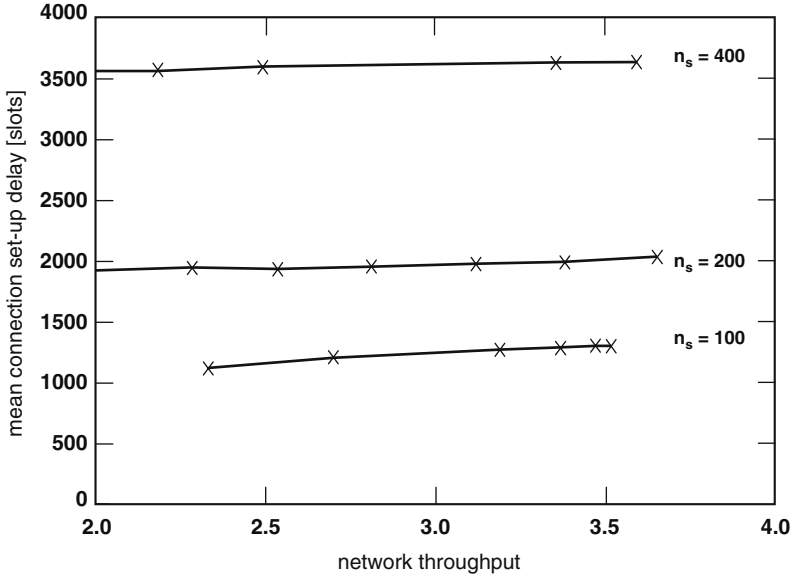

Fig. 6.10 Connection set-up delay for different ring lengths (M = 16, C = 4, r = 30%)

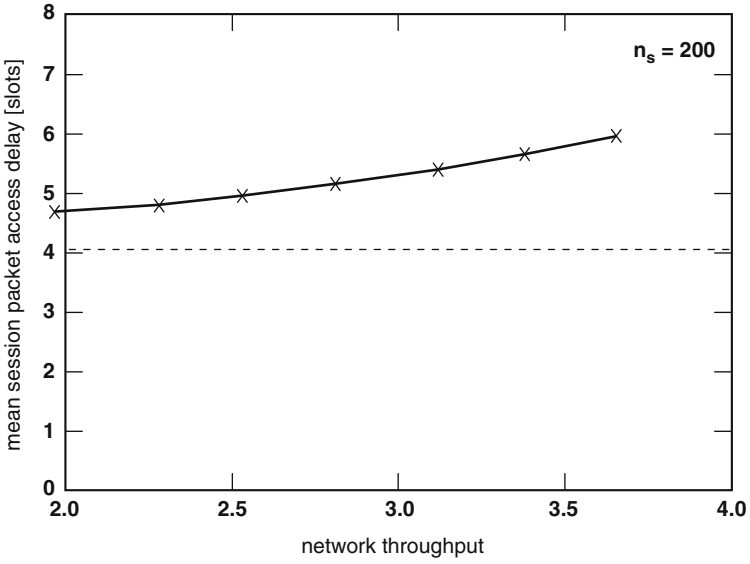

Fig. 6.11 Access delay encountered by real-time traffic (M = 16, C = 4, r = 30%, n_s = 200)

Figure 6.11 shows the mean session packet access delay defined as the delay caused by bypassing occupied slots after having initiated a real-time session. The curve reveals that only a slight increase in delays occurs for uniform traffic, i.e. is

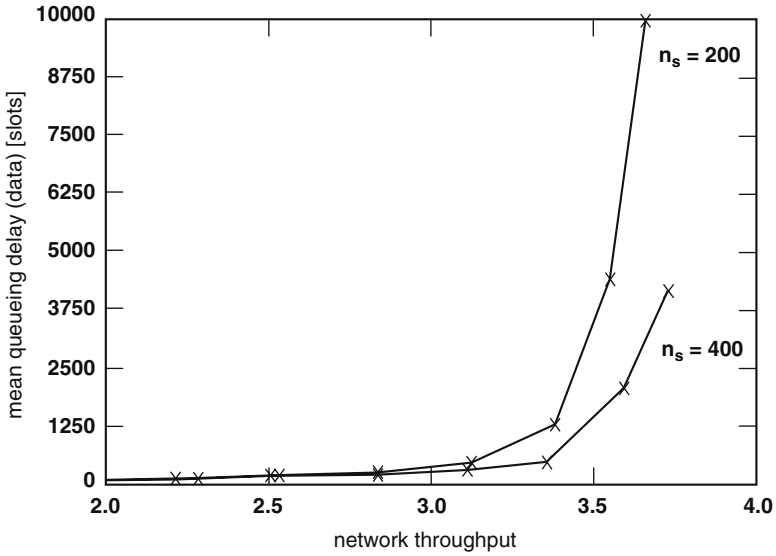

Fig. 6.12 Queuing delay encountered by best-effort traffic (M = 16, C = 4, r = 30%)

almost deterministically even in the presence of 70% data traffic load, and thus allows remarkable total network throughputs without degrading real-time performance.

Figure 6.12 illustrates the queuing delay (infinite buffer case) for data packets versus network throughput for different ring lengths (i.e., n_s = 200 and 400).

With the proposed M-ATMR fairness protocol almost equal access delay and node throughput distribution can be achieved [Bengi01], completing the QoS aware access control architecture for slotted multi-hop WDM ring networks.

6.3.5 Summary

A complete medium access control architecture efficiently supporting real-time and data services in slotted WDM ring networks has been developed. Applying distributed control and allowance for much more nodes than wavelength channels, render the proposal practically scalable to different network sizes and the performance studies prove that also performance is rather scalable in terms of network size neither discriminating real-time QoS sensitive services nor the QoS insensitive data services. The presumed underlying node architecture, i.e. each node equipped with one tuneable transmitter and one fix-tuned receiver, is assumed realistic as cost for tuneable laser sources is decreasing. Enabling statistical sharing of wavelength's capacity for traffic to several destination nodes reveals an intrinsically scalable multi-hop transport system.

The random selection among concurring packets to different destinations is found to provide a satisfactory compromise between performance and implementation complexity. The connection-oriented QoS support (reservation of equally spaced slots assigned to distinct destination nodes) concurring with connection-less transmission has proven to grant sufficient (i.e. nearly deterministic) real-time performance. With the M-ATMR fairness protocol applied for best-effort traffic, i.e. the unreserved bandwidth shares, highly desirable throughput and delay fairness can be achieved.

An extension of this basic study including splitter networks to last mile line terminals all-optically connected to the WDM ring with distributed NIU control is presented in [Aleksic07].

6.4 Efficient Support for Multicast and Peer-to-Peer Traffic

6.4.1 Multicast Traffic

Today many services delivered to end users, such as video and audio streaming, are based on multicast traffic. Thus, next generation PONs could be able to efficiently support this kind of traffic. Most PON architectures are well suited for multicast traffic and real-time services because of their broadcast nature and of the direct physical links from the OLT to the ONUs, without any processing and switching devices (i.e. routers or switches) along the path. This largely avoids unnecessary delays and buffering.

In the WDM case, if PONs are reconfigurable as described in section 2.2.6, by tuning multicast groups to the same wavelength, bandwidth can be more efficiently used, since one single data stream can be transmitted to the whole group avoiding multiple copies. Basically, multicast traffic is to be taken into account when deciding PON topologies. Efficient bandwidth use can be obtained by building traffic-matched topologies. For example, in the case of video distribution, a whole wavelength could be used for the sport events, another one for the movies' stream and so on.

Therefore, a simple solution to support multicast traffic could be to equip ONUs with a dedicated receiver for this traffic. In this way, the PON could allocate some wavelengths to deliver only multicast traffic; thus, the problem would be to find out the minimum number of wavelengths needed in order to support multicast traffic. This solution would imply that ONUs should have at least two receivers, one for multicast traffic and one for unicast traffic. From a scheduling point of view, this solution would imply that the support of unicast and multicast traffic would be completely independent, and that two logical PON topologies would be built over the PON: one for unicast traffic, and another for multicast. However, if multicast and unicast traffic share the same receiver, the logical PON topology would be just one and should take into account both traffic patterns. Algorithms for finding logical PON topologies under both patterns are still an open issue.

6.4.2 Peer-to-Peer Traffic

Many traffic studies show that peer-to-peer applications are becoming increasingly popular. PON architectures need therefore to support peer-to-peer applications, which require large bandwidth, and make the traffic pattern more symmetric between upstream and downstream paths with respect to other streaming or Internet client-server applications.

A possible approach to deal with the increased bandwidth requirements of peer-to-peer traffic, and with its symmetry, is to introduce (C)WDM in the upstream path, by equipping ONUs with slow tuneable transmitters, and the OLT with an array of fixed receivers, as sketched in Fig. 2.14 (and described in section 2.2.6). Again, a decision problem arises for deciding to which wavelength ONU transmitters should be tuned; however, while for downstream traffic the OLT knows the traffic matrix, for upstream traffic this information is distributed among nodes.

Moreover, if WDM is introduced in both downstream and upstream paths it means that scheduling algorithms at the OLT should also be adapted. Besides, it is important that these algorithms take also into account multicast and peer-to-peer traffic.

For peer-to-peer traffic, it is reasonable that intra-PON traffic, i.e., traffic coming from one ONU and directed to another ONU of the same PON, should be forwarded by the OLT back to ONUs as soon as possible. This goal can be reached providing a fast switching at the MAC layer. For example for EPONs, some slots (each slot can store several Ethernet packets) of the TDM stream can be reserved for peer-to-peer traffic; an efficient scheduling algorithm can be applied directly on these TDM slots, avoiding to receive individual Ethernet packets at the OLT.

In general, the optimal solution would be to jointly schedule upstream and downstream transmissions, i.e., to couple the two normally disjoint upstream/downstream scheduling problems.

Chapter 7
Metro-Access Convergence

Carlos Bock, Jose A. Lazaro, Victor Polo, Josep Prat, and Josep Segarra

7.1 Core-Metro-Access Efficient Interfacing

Large optical networks are typically partitioned into core (inter-city) and metro (intra-city) sub-networks, and the last portion of the telecommunications network that runs the services to the home or business is the access network. The technologies for core, metro and access sub-networks will provide rapid provisioning of connections within each sub-network (Fig. 7.1). However, it is essential that the core, metro and access sub-networks are able to work interconnected to release the fast provisioning potential of these sub-networks, since a large part of the anticipated connections will need to traverse both core and metro sub-networks and finally reach the access. This requires signalling and routing information exchange between the different sub-networks. The inter-networking, and particularly the routing information exchange, is the focus of the core-metro-access interfacing.

While access and metro sub-networks handle local traffic and offer service-sensitive aggregation and service-specific features, the core network transports relatively homogeneous connections across long distances, thus the core network may be based on different technology than the access and metro sub-networks. Due to this fact, simpler optical nodes based on low cost or functionality may be used in access and metro transport whilst long-haul networks may involve high performance on the optical spectral characteristics of the devices. These differences may result in some specific requirements on the routing information that need to be distributed within the core, metro and access sub-networks. However, there are fundamental requirements on the routing information that needs to be exchanged between the sub-networks [Wang01].

IP-based protocols to control optical networks are introduced with a solid distributed control plane for packet networking, and the flexibility of the underlying protocols and mechanisms allows for adaptation to transport networks. The Internet Engineering Task Force (IETF) is currently developing the control plane protocol Generalized Multi-Protocol Label Switching (GMPLS) [Berstein00], based on the Multi-Protocol Label Switching (MPLS) architecture [Rosen01]. Using GMPLS will give service providers the flexibility of inter-working equipment from different

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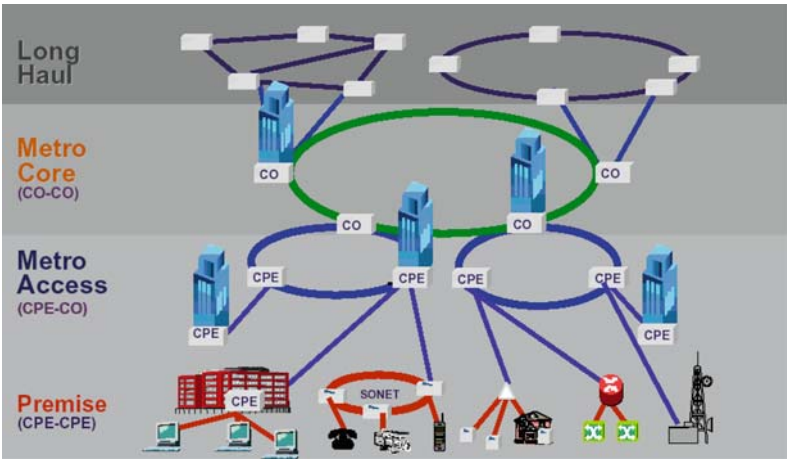

Fig. 7.1 Core-metro-access subnetworks

vendors. Given that GMPLS is based on extensions to IP protocols, there must be an information exchange between the access/metro sub-networks and the core network based in IP routing protocols.

7.1.1 Optical Node Implementation

Due to the inherent network resilience, the ring topology is assumed in the metropolitan sub-network [Herzog04], while in the access the ring may be combined with the tree topology. The optical node functionality depends on the interface role. Optical Cross-Connect (OXC) and Reconfigurable Optical Add/Drop Multiplexer (ROADM) allow input channel ports being routed to output channel ports by means of optical switches in a matrix, having the OXC a greater cross-connection capability and flexibility, but at higher cost. The ROADM with few channels dropped/inserted may be the solution for interconnection of the access with the metro rings whilst the complex OXC can serve the internetworking metro-core.

In an access network, a simple OXC architecture can also be used [Segarra04] for managing several Passive Optical Networks (PONs), so the data laser sources and the receivers can be shared by thousands of users achieving better device efficiency. Anyway, the PONs can be connected with ROADMs in a metro ring to reach a distant router controller in an all-optical connection, but this architecture has a distance limit, not only due to power budged but also due to signalling propagation delays in the Dynamic Bandwidth Allocation (DBA). The distant router controller will interoperate with the next hierarchy metro or core network exchanging routing information.

7.1.2 All-Optical Interfacing Access-Metro Architectures

Optical Burst Switching (OBS) allows large optical bursts composed by several IP packets, thus greater transmission efficiency with less tuning and synchronization is attained. To reach a distant router in an all-optical data transmission with efficient switching, an Optical Burst Switching Multiplexer (OBS-M) is introduced (Fig. 7.2) with Wavelength Converters (WCs) [Segarra04]. The distant router works with the core network interchanging routing information and adapting the different access-metro-core protocols.

This architecture can manage several (*Q*) Optical Line Terminals (OLTs) in a *1xR* Arrayed Waveguide Grating (AWG) based access topology, serving a total of *QxR* Optical Network Units (ONUs). In the uplink the *N* data photodiodes (PDs) are substituted by *N* WCs that convert the *R* wavelengths available in the AWG ports provided by the ONUs to *N* up wavelengths. In downlink *N* wavelengths generated in the distant router are converted to the *R* wavelengths accordingly to the proper ONU destination. The WCs can be Optical/Electrical/Optical (O/E/O) or all-optical. The router may be located at hundreds of kilometres from the OBS-M, with optical amplification, while the ONUs may be located at a maximum of 20 km from the OBS-M.

The burst scheduler for uplink is located in the OBS-M, so the scheduler-ONU distances for the DBA module are kept low and the signalling delays are in a good range. The control photodiodes (PD_c) receives the up requests and the scheduler handles the WCs and the OXC to up transmit the data bursts, so the DBA protocol

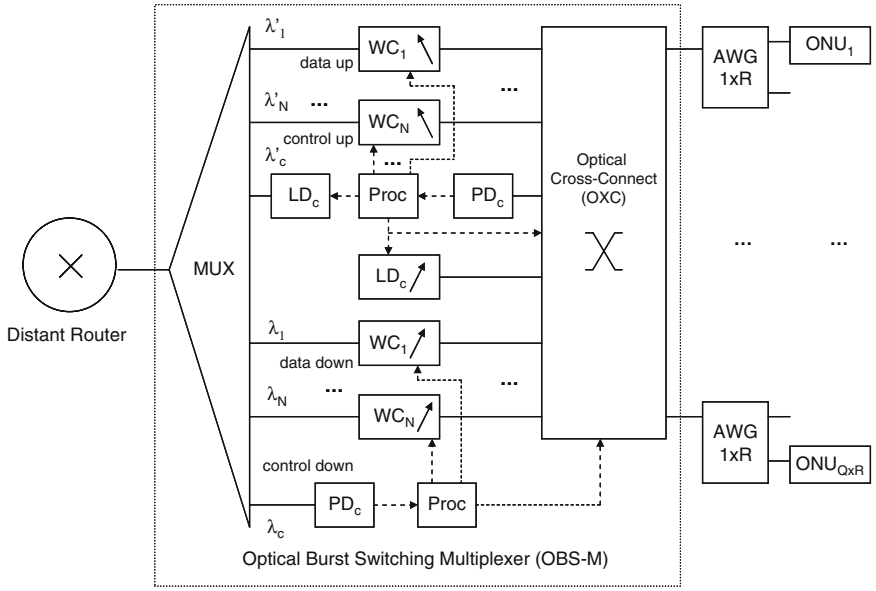

Fig. 7.2 Optical Burst Switching Multiplexer for distant router

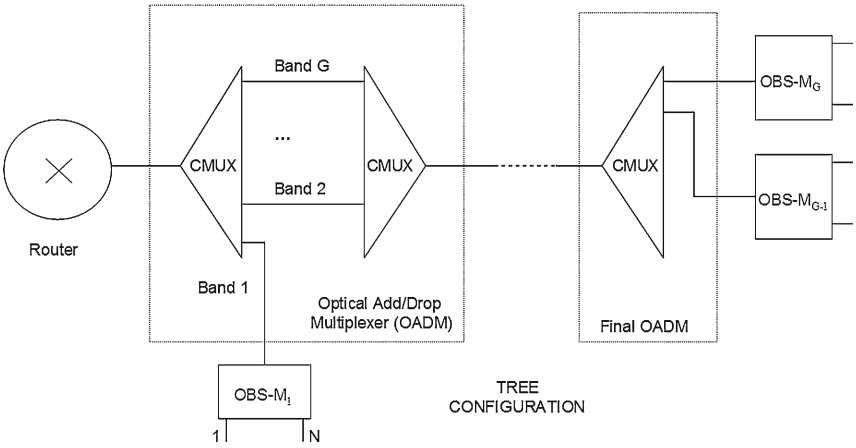

Fig. 7.3 Tree architecture with a distant router and reconfigurable Optical Add/Drop Multiplexers

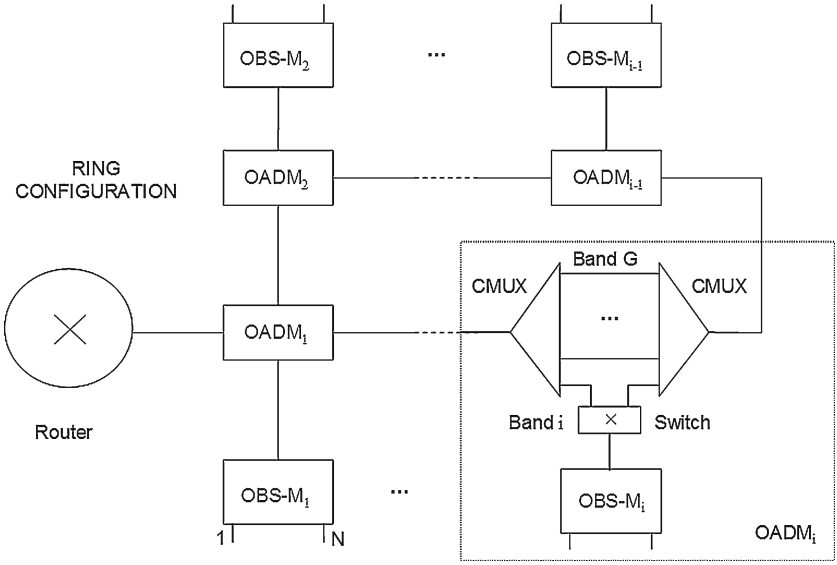

Fig. 7.4 Metro ring architecture with a distant router and reconfigurable Optical Add/Drop Multiplexers

manages limited distances from OBS-M to the ONUs in order to keep short signalling times. An up-control wavelength announces the up-traffic to the router.

For downlink, the data bursts and the wavelength assignment are generated by the distant router. A down-control wavelength is received in advance at the OBS-M, carrying the information to handle the WCs and the OXC to route the data bursts to

the destination ONUs. The anticipated time must be enough to let the OBS-M process the down control and operate the WCs and the OXC.

The topology is scalable in tree configuration with ROADMs handling up to *G* OBS-Ms, each one with a band transporting *N + 1* (data + signalling) up-wavelengths and *N + 1* down-wavelengths (Fig. 7.3). The number of wavelengths covered by the router is *2(N + 1)G*. The total available ONUs in the metro network will be *M = GxQxR* (e.g. 768 = 4 × 8 × 24) and if a splitter-by-*S* is used at the AWG output *M = GxQxRxS* (e.g. 3,072 = 4 × 8 × 24 × 4). The ROADM allows to add/drop different numbers of wavelengths depending on the traffic and ONU deployment.

The architecture is also extended to a ring topology, which allows resilient protection. In all router configurations the burst scheduler for uplink is located at each OBS-M, while for downlink the management is situated in the distant router (Fig. 7.4).

7.2 Optical Burst Switching in Access

OBS was initially proposed for routing in the optical core networks [Qiao00]. Data packets assembled into variable bursts at the edge routers are launched to the core routers when a maximum burst length or time limit is reached. With this transfer mode, large optical bursts composed by several IP packets are allowed, thus achieving greater transmission efficiency with less tuning and synchronization. In this unconfirmed OBS, a control for resource reservation is sent an offset time before data bursts, which, without assured lightpath, may be lost due to collision, needing then a retransmission. Another sort of OBS is Wavelength Routed Optical Burst Switching (WROBS) [Duser02]: an end-to-end reservation between a centralized control node and the edge router is assumed; the bursts are transmitted over a guaranteed on-demand routed end-to-end lightpath and data losses can occur only at the edge routers due to buffer overflow. In the access networks, the propagation time is much lower than the aggregation time, so WROBS is selected in the PON because an end-to-end signalling assures transmission without collisions and well adapts to the tree topology and proposed DBAs [Segarra05].

7.2.1 Medium Access Control Protocol and Dynamic Bandwidth Allocation

In the OBS PON architecture, a centralized scheduler at the OLT is used for the Medium Access Control (MAC) protocol, which combines Time Division Multiplexing (TDM) and WROBS for downstream and upstream data burst transmission. In the downstream direction, the OLT has the full bandwidth to transmit data bursts and control packets to the ONUs whenever it needs. On the other hand, in the upstream direction, a DBA module with a pre-transmission cycled control slot monitoring the ONUs traffic status arbitrates the shared medium, avoiding collisions by granting up transmission windows to the ONUs.

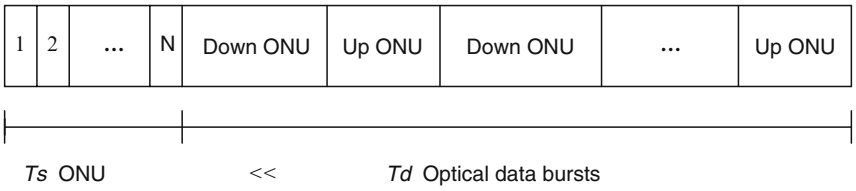

Fig. 7.5 Time resources for control signalling and variable data bursts

The control messages will be cycle based, where a cycle is defined as the elapsed time between two pollings of the same ONU. The cycle size can either have fixed or variable length, limited to an upper bound to guarantee a maximum latency. A variable polling cycle accommodates changeable traffic characteristics, thus providing a better efficiency. The cycle length T_c is divided into two periods: an update signalling period T_s and a dynamic transmission period T_d (Fig. 7.5). The update period is divided into N equal fixed control slots, being N the number of the ONUs. In the update period T_s, the active ONUs are polled consecutively to inform their status to the OLT in request messages. The OLT gets a global knowledge every cycle. The transmission period T_d is a wide window used for upstream and downstream data transmission. With all ONUs in the active status, the duration of the cycle is:

$$T_c = T_s + T_d = N(t_c + t_{LD}) + T_d$$

where t_c is the ONU slot control time and t_{LD} is a guard time separating two consecutive slot times to account for the laser on/off switch. The OLT knows every ONU Round Trip Time (RTT), so the optical signals for the up control slot and data up transmission are generated in the OLT in such a way that the collisions are avoided in its up reception at the OLT. In this centralized scheme, all the control for down and up data transmission remains at the OLT, which is aware of the complete network traffic needs, thus QoS can be provided with differentiated Classes of Service (CoS) and conformed Service Level Agreement (SLA). The OBS transfer mode can also be used to interface the access with the metro/core domain in an all-optical data burst end-to-end transmission, providing great transmission efficiency.

7.2.2 Optical Burst Switching and Traffic Aggregation Strategies for Access Networks

Input user traffic must be classified according to its destination in burst aggregated queues which, managed by an assembling algorithm, generate optical bursts to be launched to the network, thus each burst assembly queue is associated to a destination. QoS can also be considered, so each destination has an assembling queue for every CoS. It is assumed that the data rate of the user's arriving packets is much lower than the bandwidth available of the network and that the queuing architecture has full access to wavelength capability.

The fundamental statistic properties of the aggregated traffic such as burst length distribution, inter-arrival time distribution, as well as correlation structure depend on the burst assembly algorithms. Three basic algorithms have been studied [Yu02], [Yuang02]:

- Algorithm I: Fixed-Time-Min-Length Burst Assembly. Is a Timer-based mechanism. Uses a fixed assembly time as the primary criteria and it requires each burst size to be larger than a minimum length b. It sends the burst when a time window t_{edge} is reached if the burst is smaller than the minimum length it is padded to attain the minimum size.
- Algorithm II: Max-Time-Min-Max-Length Burst Assembly. Is a Threshold-based mechanism. Uses the maximum assembly length as the primary criteria. The burst is sent as soon as a maximum length B is reached, otherwise the burst is sent when a large time window t_{edge} is attained and padded to a minimum length b if that is not reached.
- Algorithm III: Hybrid Timer/Threshold-based mechanism. Both fixed assembly time t_{edge} and threshold maximum burst length B parameters are set for launching the burst as the earliest parameter is achieved. Both parameters can also be varied according the input traffic load in an adaptive hybrid burst assembly.

The aggregation time window t_{edge} may vary from 10 to 20 ms for higher priority classes, and can be set from 50 to 500 ms for CoS in order to keep the maximum total latency within a certain limit. The maximum burst length depends on the SLA and also on the total network delay; under low input load a long period will be needed to reach the length threshold, so the first algorithm or the hybrid is preferred.

It is demonstrated from both theoretical and empirical results that after the assembling of either Short Range Dependent (SRD) or Long Range Dependent (LRD) traffic the inter-arrival time and the burst length statistics approach the Gaussian distribution [Yu02] due to the effect of multiplexing multiple sources, as consequence of the central limit theorem. At light load condition under SRD or LRD traffic in the input, the assembled traffic will remain SRD or LRD unchanged, respectively, but smoother in short range approaching Gaussian.

Under heavy load and SRD the assembled traffic will become constant rate because of the smoothing effect during the short time period of assembling. With heavy load LRD traffic and Algorithm I, in the busy period the assembled traffic will become constant rate and in the silent period the assembled traffic will result Gaussian. However, for burst assembly Algorithm II, using the buffer to smooth the traffic, the effect is to shift the traffic load accumulated in a busy period to the following silent period and the assembled traffic will still approach the constant rate traffic, but with the removal of the LRD individual packets will suffer a long delay. Nevertheless, if the multiplexing level is low for an end user to be served, as may be expected in an access network, the SRD and the LRD statistics will not significantly change and the traditional Poisson and LRD models may apply.

7.2.3 *Optical Burst Switching, Queue Management and Priority Queuing for QoS*

Bandwidth management of different CoS plays an important role in supporting QoS [Blake98]. Scheduling data packets is required at the OLT for downstream and at the ONUs for upstream. We consider three CoS priorities: *P1*, *P2* and *P3*; with *P1* the highest priority and *P3* the lowest. They can deliver voice (*P1*), video stream and priority data (*P2*) and best-effort data (*P3*) allowing mapping on Expedited Forwarding (EF), Assured Forwarding (AF) and Best-Effort (BE) P802.1D classes of DiffSer. The arriving packets are classified and positioned into the appropriate priority queue (Fig. 7.6).

Each ONU keeps three separate CoS priority data queues sharing the same buffer, thus the incoming data packets are classified and placed into their proper queue. If an incoming packet of high priority finds the buffer full, then it displaces a packet of lower priority. Moreover, an incoming low priority packet with the buffer full is discarded. In addition, a monitored transfer policing is needed to control the maximum traffic that each user is permitted to send to match its Service Level Agreement (SLA). The OLT maintains also three CoS priority data queues for every ONU, a total of *3N* queues sharing a unique buffer, with the same rules described for the ONUs.

In the OBS PON scheme, the bursts are generated at the priority queues of each ONU and at the OLT. The packets are aggregated into bursts until a maximum aggregation time t_{edge} or a maximum burst size *B* is reached. Then a priority *Pi* CoS transmission request is generated. The maximum aggregation burst time t_{edgei} may be different for every *Pi* CoS, in such a way that the higher priority class will have the lower t_{edge1} in order to guarantee the least delay limit.

The incoming burst requests are placed in three CoS queues at the DBA module. A priority scheme is needed at the OLT for scheduling burst requests by the DBA algorithm to assign the available bandwidth, sharing the bandwidth resources for up

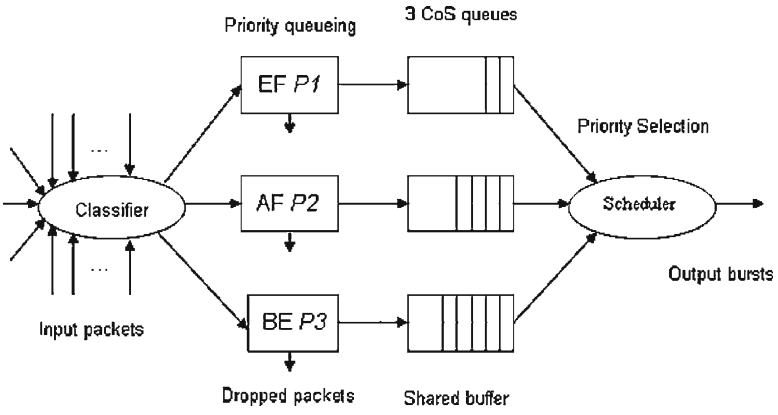

Fig. 7.6 Scheduling data bursts with three Classes of Service

and down data burst transmission. There are several mechanisms for supporting differentiated service classes, the more suitable for WROBS are:

- Strict Priority (SP) [Segarra05] queuing discipline (defined in P802.1D) is a helpful and relative simple scheme: bursts with the highest priority are selected ahead of those with lower priorities, independently of their arrival into the system, so it schedules bursts from the head of a given request queue only if all higher priority queues are empty. However, with a high load in the priority CoS, low priority CoS may experience excessive delays and increased packet loss in a resource starvation.
- Modified Strict Priority (MSP) or Priority Scheduling has been proposed [Assi03] to overcome this problem, the low CoS packets suffering a certain maximum delay are given the highest priority and the Strict Priority applies to the rest of the packets.
- Earliest Deadline First (EDF) [Chiussi98]. With this service discipline each generated data burst is associated a local delay deadline d_i depending on the CoS. The high CoS has the lower deadline and the best-effort the highest one, then the queuing bursts are served by increasing order of their deadline. EDF is known to be the optimal scheduling policy, but due to the random memory access it is difficult to implement in a fast hardware.
- Rotating Priorities Queues (RPQ) [Wrege97] emulates the EDF using Strict Priority queues, interchanging the bursts in the queues in a dynamic manner with a periodic rearrangement. Queue rotations can be implemented by updating a set of pointers and the efficiency can be close to the complex EDF, but only little computational overhead is needed.

The DBA module will apply a CoS priority mechanism to the arrived requests from the ONUs and the OLT to allocate properly the down and up data variable bursts in the available bandwidth, therefore a QoS guarantee wil be provided.

7.3 Sardana Network: An Example of Metro-Access Convergence

The Sardana network is an example of metro-access integration. It is an FP7 project under development that will run from 2008 until 2010.

Sardana is based on an access network which is predicated on the following principles:

- Up to 1,024 users per PON segment
- 10 Gbps data rate
- Remote passive amplification
- Wavelength-agnostic customer units

Two architectures have been developed following these principles: the first one, based in a single fibre ring, is adequate for non-reflective ONUs; the second one, based in a double fibre ring, is appropriate for reflective ONUs.

7.3.1 Single Fibre Ring Sardana

Figure 7.7 presents the network topology. Two PON trees are connected to the central distribution ring by each Remote Node (RN), as will be discussed below. Downstream and upstream are wavelength multiplexed, so each RN drops two downstream wavelengths and inserts two upstream ones from/to the ring. Thus, the relationship between the number of RNs (N) and the number of wavelengths (M) is a fixed design parameter, which is $M/N = 4$.

The remote node design is presented in Fig. 7.8. RNs are based on three power couplers and wavelength filters. Power couplers that are connected to the ring are

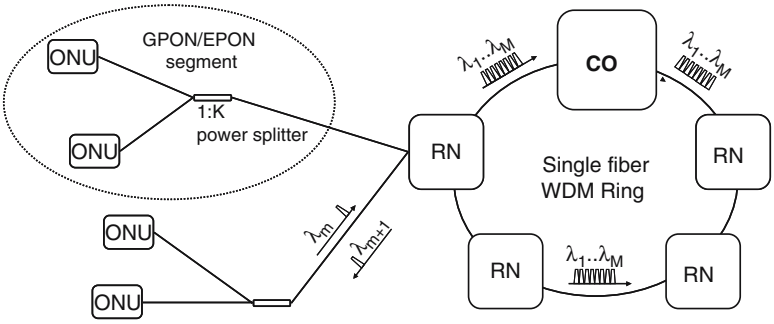

Fig. 7.7 Network architecture of the single fiber ring Sardana

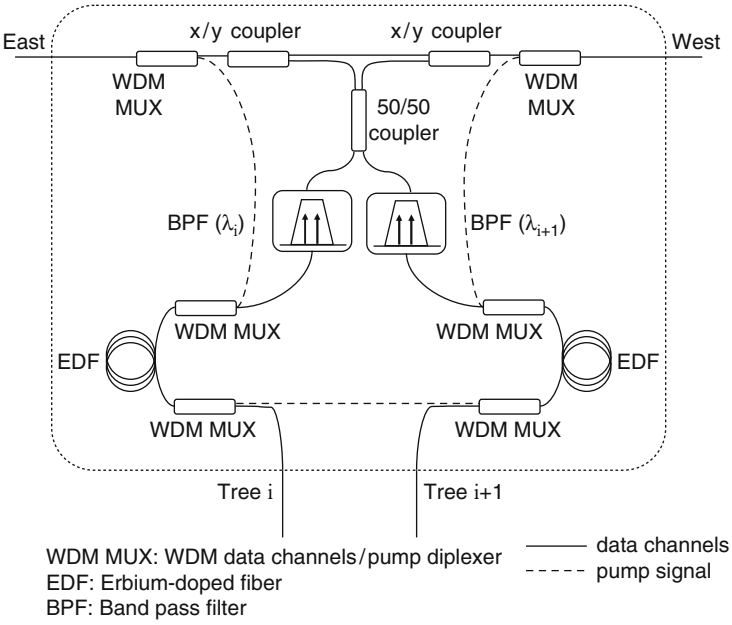

Fig. 7.8 Remote Node design and wavelength routing profile

x/y ($x + y = 1$), which are designed depending on the number of remote nodes to minimize power losses. The design parameters x and y are fully analyzed in section 7.4. The third coupler, which ensures connectivity to the two directions of the ring, is 50/50. At the output of the 50/50 coupler, two filters (thin-film specifically in our setup) select the specific downstream and upstream wavelengths for each of the two tree PON sections that are connected to the RN. The reason to connect two PON segments to each RN is to take advantage of the two output ports of the 50/50 coupler that is used for resilience purposes. With this design, the remote node performs transparently independent of the direction of the incoming downstream light and transmits upstream signal to both directions of the ring. This feature is the key to provide resilience in case of a fibre cut in the central ring.

At the Central Office (CO), each Remote Node Interface (RNI) is composed by two lasers and four photo-receivers, as presented in Fig. 7.9. Each laser is coupled to both directions of the ring by means of an optical interleaver. By fine adjusting of the laser transmission wavelength the interleaver routes the signal to the direction of the ring that maximizes the power budget margin, depending on the number of passed remote nodes. This can be done by monitoring the upstream power levels and switching to the direction that offers higher received power. The redundant photo receivers detect the incoming signals from both directions of the ring and select the one with better power level. This feature also enables to offer resilient capabilities. In case of a fibre cut, the laser will change the transmission wavelength to select the only possible direction to serve the RN while one of the photo receivers will still receive the upstream transmission signal.

On the side of the ONU, the only change that is required to a commercially available Ethernet and Gigabit Passive Optical Network (EPON/GPON) ONU is

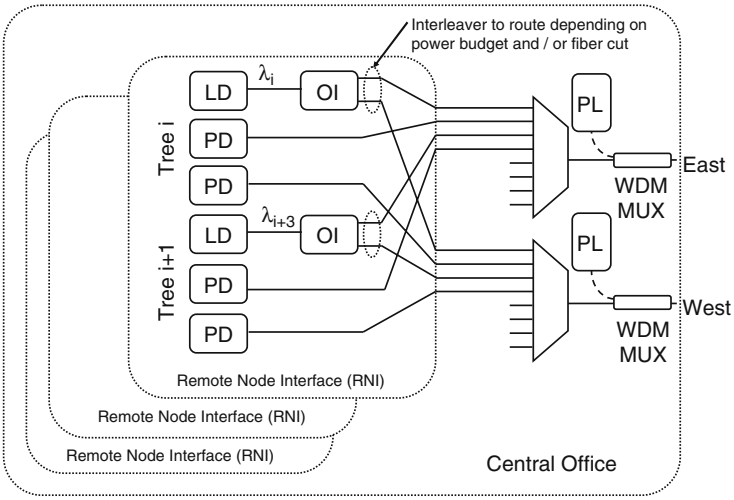

Fig. 7.9 Central Office remote node interfaces

the substitution of the 1,310 nm upstream transmission laser by a laser to transmit on the wavelength assigned to that specific PON segment. The rest of the equipment and logical control remains invariant.

An important design parameter to make the network compatible with EPON/GPON standards is related to power budget restrictions. In addition to the tree splitting stage, the proposed network adds pass-through and dropping losses together with insertion losses of the wavelength filters. To overcome those losses in the main ring while keeping a passive outside plant, remote amplification is convenient [Lazaro06]. For this purpose, two 1,480 nm pump lasers (one at each ring direction for resilience) are included in the CO of Fig. 7.9.

7.3.1.1 Resilience and Power Budget Optimization

The proposed network design provides resilience and power budget optimization features by means of an optical interleaver and fine adjustment of the transmission wavelength at the RNI of the CO. Each remote node has a default path which is selected when the system is powered up. This default path corresponds to the path with lower losses and is determined by monitoring the received power coming from both directions of the ring. This determines the default transmission wavelength. In case of a fibre cut affecting the connectivity to the RN, the RNI slightly changes the transmission wavelength and reaches the RN though the other direction of the ring.

The procedure is described in Fig. 7.10, together with the wavelength plan for upstream and downstream transmissions. The network interleavers have to be chosen to be half of the wavelength channel spacing so both default/protected and upstream transmission wavelengths pass through the filters to reach the appropriate network subsegment. The selection of the output port of the interleaver is done by finely tuning the laser emitting wavelength. This functionality does not require the use of a tuneable source as the tuning can be done by adjusting the temperature of the laser.

7.3.1.2 Network Analysis

An analysis of power budget margins was performed to demonstrate the feasibility of the proposed network. As Wavelength Division Multiplexing (WDM) is totally transparent to TDM/TDMA protocols of G/EPON, the optical experiments have been addressed to verify correct reception of pattern-generated data streams while calculations have been done to verify correct power levels at the receivers.

Network Dimensioning

The number of remote nodes (N) is a key parameter in terms of network performance because it determines the number of wavelengths (M) of the network and thus, the total network capacity. Other parameters that also affect on the network performance is the data rate and the splitting ratio (K) of the network subsegments but

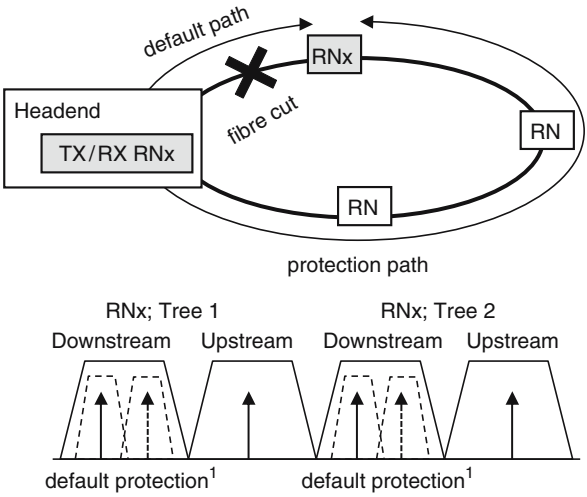

Fig. 7.10 Power budget optimization and resilience mechanisms

those parameters are intrinsic of each network subsegment and do not affect the number of nodes.

The total number of users (U) is determined by the number of remote nodes and the splitting ratio in the network subsegment. If one supposes that the splitting ratio is the same for all the remote nodes it leads to $U = 2\,N\,K$ and both, N and K affect on the power losses, total network capacity and bandwidth per user. When N increases, the network can offer more bandwidth because more wavelengths are transmitted but at the same time, power losses increase. In order to minimize outside plant power losses, total link losses in the outside plant, presented in Eq. (7.1), should be minimized.

$$L_T = (N-1)\cdot 20\cdot\log x^{-1} + 10\cdot\log y^{-1} + N\cdot L_{EX} + 3\cdot\log_2 K + L_S \tag{7.1}$$

where L_s are additional losses due to fibre, insertion losses of optical equipment and wavelength filtering in the outside plant, typically ranging from 7 to 13 dB depending on the fibre span and installed conditions. x and y are the coupling factors for the coupler pass-through and drop branch respectively. The relationship between them is $x + y = 1$. Finally, L_{EX} represents coupling excess losses at each RN due to manufacturing, aligning and installing processes, typically 0.3 dB per RN. The number of N that minimizes (7.1) is:

$$N = \frac{3}{\ln 2}\cdot\left(20\cdot\log x^{-1} + L_{EX}\right)^{-1} \tag{7.2}$$

The most important conclusion of (7.2) is that the optimal number of nodes is independent from the total number of users (U). This means that U is just limited by the power budget and that to increase the number of users it is more efficient, from the view of the power losses, to increase the splitting ratio than to insert additional remote nodes. However, this reduces network capacity because then the sharing factor per laser increases. Therefore, when designing a network, a compromise should be met between optimizing power losses and optimizing network performance. Figure 7.11 presents losses as a function of the number N for different coupling factors.

From (7.1), it can be demonstrated that when K is constant for all the RN, an increase of the number of users (U) in the system for a given number of RNs adds a vertical offset to power losses and thus reduces power budget margin in a constant value. It can be also seen from Fig. 7.11 that when coupling factor x tends to 1 the curve flattens and increasing the number of RNs does not affect power losses dramatically. Therefore, if it is assumed the network will grow in the number of remote nodes due to an increase in the number of users or in the network bandwidth requirements, it is the long term preferred option to choose x close to 1.

In a realistic case, the number of RN (N) is also determined by the geographical distribution of end users so the best option to design the network is to fix the number of RN (N) and the network bandwidth per user and to calculate the other design parameters accordingly.

Network capacity is related to the splitting ratio (K) in each network subsegment. Each wavelength is assigned to a network subsegment, thus the network performance for a given splitting ratio is just related to the chosen PON protocol. Based on [Angelopoulos04], the bandwidth per user for $K = 16$, $K = 32$ and $K = 64$ is respectively 125, 62.5 and 32.25 Mbps in a GPON at 2.5 Gbps in case of network

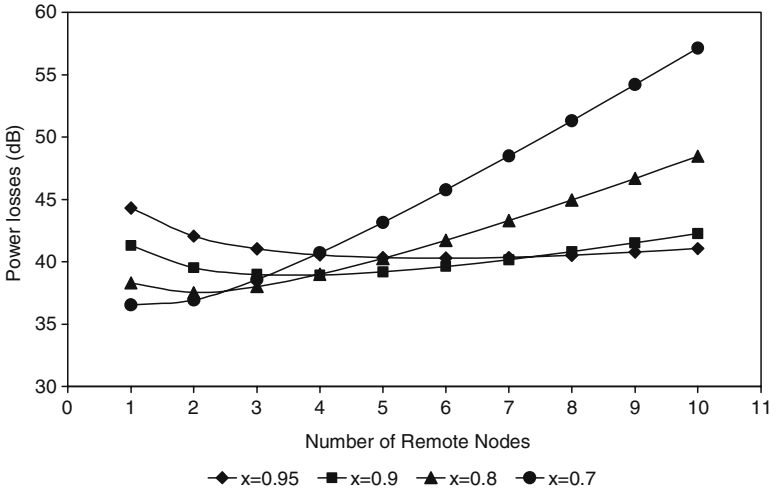

Fig. 7.11 Power losses as a function of N for x = 0.95–0.7 and with L_S = 10 dB and L_{EX} = 0.3 dB

saturation. $K = 64$ is the largest splitting ratio that GPON supports up to now, hence in case we want to exceed this value, the addition of remote nodes is obligatory. Table 7.1 presents the total number of users depending on the number of remote nodes for different values of K.

The last parameter to be optimized is the coupling factor of the couplers at the main ring. Minimizing L_T with respect to x in (7.1) leads to the following results

$$x = \frac{2 \cdot N - 2}{2 \cdot N - 1} \quad y = \frac{1}{2 \cdot N - 1} \tag{7.3}$$

which are represented in Fig. 7.12.

Results from Fig. 7.12 show a tendency to stabilise for $N \geq 4$. This is consistent with the results of Fig. 7.11 and confirms that the use of commercial 90/10 ($x = 0.9$, $y = 0.1$) couplers offers a good compromise between having a flexible and scalable solution while keeping the total losses low.

Finally, the results from Fig. 7.11 do not take into account transmission constraints and losses. Additional power losses due to passing through RNs reduce

Table 7.1 Number of users depending on K and N

		# of users		
# RN (N)	# Wavelengths	K = 16	K = 32	K = 64
2	8	64	128	256
4	16	128	256	512
8	32	256	512	1,024
16	64	512	1,024	2,048

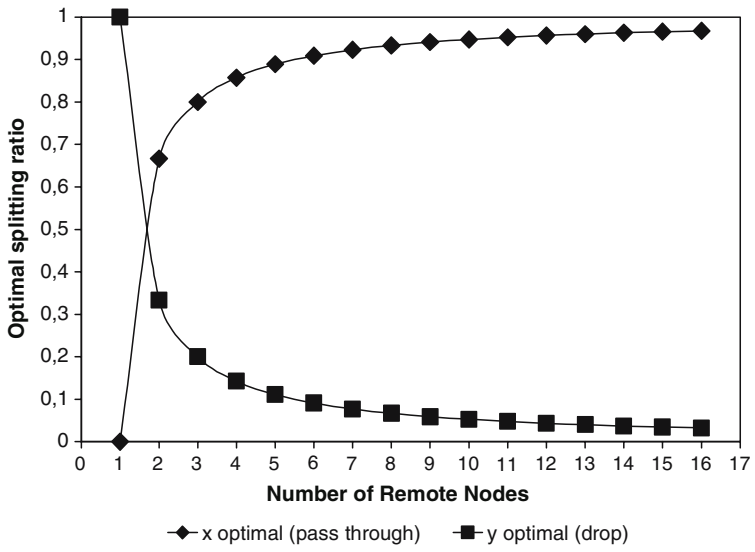

Fig. 7.12 Optimal splitting factors as a function of the number of remote nodes

power budget and limit the network size. By working out (7.1) incorporating the remote amplification gain (G) and restricting losses to be less than power budget (PB) we can express it as:

$$PB \geq (N-1)\cdot 20\cdot \log x^{-1} + 10\cdot \log y^{-1} + N\cdot L_{EX} + 3\cdot \log_2 \frac{U}{2N} + L_S - G \tag{7.4}$$

Values of PB are in the range of 20–30 dB for commercial equipment following both ITU/IEEE (International Telecommunication Union/Institute of Electrical and Electronics Engineers) recommendations, proposing PB = 20 dB for Class A to PB = 30 dB for Class C equipment. Figure 7.13 presents the power budget margin depending on K and G using the optimal design parameter of x and y, L_S = 10 dB and L_{EX} = 0.3 dB. Horizontal lines represent the PB for different classes of equipment.

All the points that are above the class A/B/C lines correspond to combinations that can be deployed using Class A/B/C equipment. Using Class C equipment offers a vast number of combinations but this equipment is also more expensive than Class A devices. There is also a balance between remote amplification gain, number of nodes and class of equipment to achieve a valid configuration. For a number of nodes $N > 8$ the use of G = 20 dB and class C equipment is almost mandatory but for smaller configurations, a more cost effective approach can be implemented.

As an example, if the deployment consists in an access network to offer service to 1,024 users, the network would be optimally deployed using a splitting ratio of K = 64 and N = 8. This would lead to an optimal coupling factor of x = 0.94;

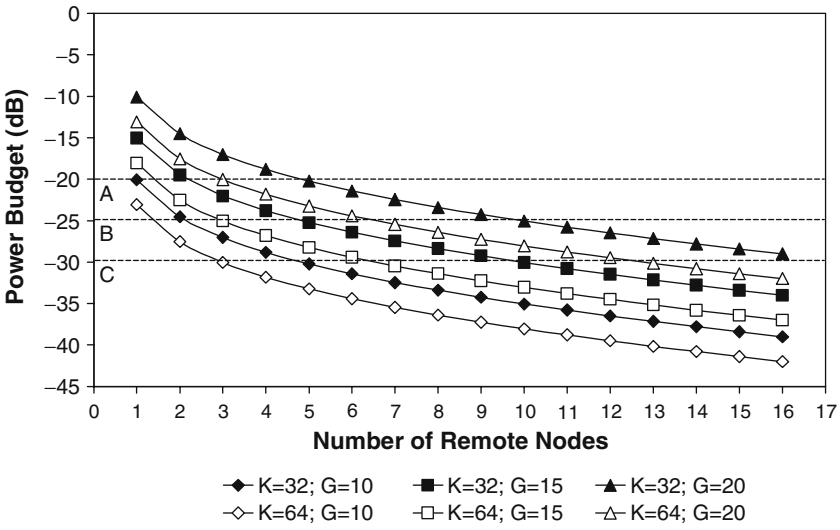

Fig. 7.13 Total number of users as a function of G and K

$y = 0.06$ (typically 0.9/0.1 couplers will be used). To achieve correct transmission, we have to amplify with $G = 20$ dB and use Class C equipment.

Remote optical amplification leads to lager *PBs* in PONs, but it also produces a reduction of the Optical Signal to Noise Ratio (OSNR). Making use of [Desurvire02] and results form (7.1), it can be deduced that the OSNR is always higher than 26 dB for the downstream and higher that 34 dB for the upstream. Such OSNR values do not significantly affect the sensitivity of the receivers which is still mainly limited by thermal noise and being the *PB* calculations still valid.

7.3.2 *Double Fibre Ring Sardana*

The proposed Single fibre Advanced Ring-based Dense Access Network Architecture (Sardana), shown in Fig. 7.14, is based on a WDM double fibre ring with single fibre wavelength-dedicated trees connected to the main ring at the RN. Two passive optical networks with trees topology are connected to each RN with a splitting ratio of 1:*K* as shown in Fig. 7.14, where the number of users *K* can be flexible. Each tree shares an optical channel in a TDM basis and due to that, each RN has to drop and add signals at two dedicated wavelengths.

The maximum number of users served by the network is then:

$$U = 2\,R\,N\,K \tag{7.5}$$

limited by the available power budget and the link loss between CO and ONU, respectively.

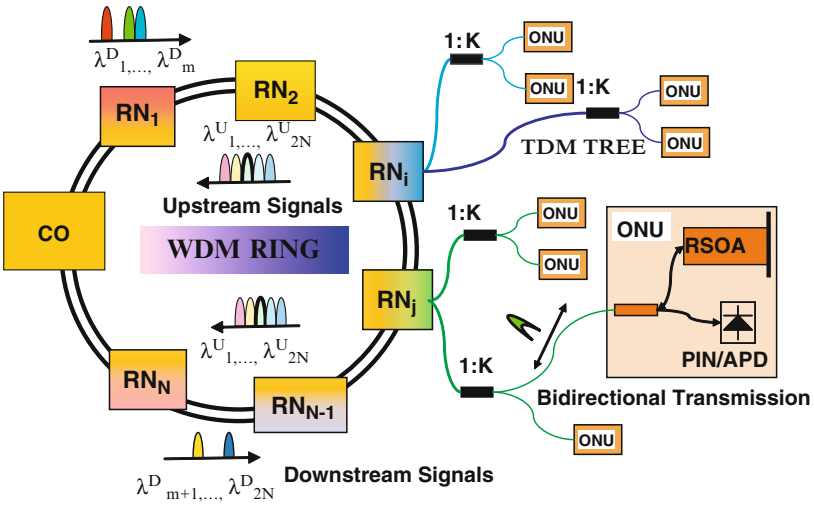

Fig. 7.14 Network architecture of the double fibre ring Sardana

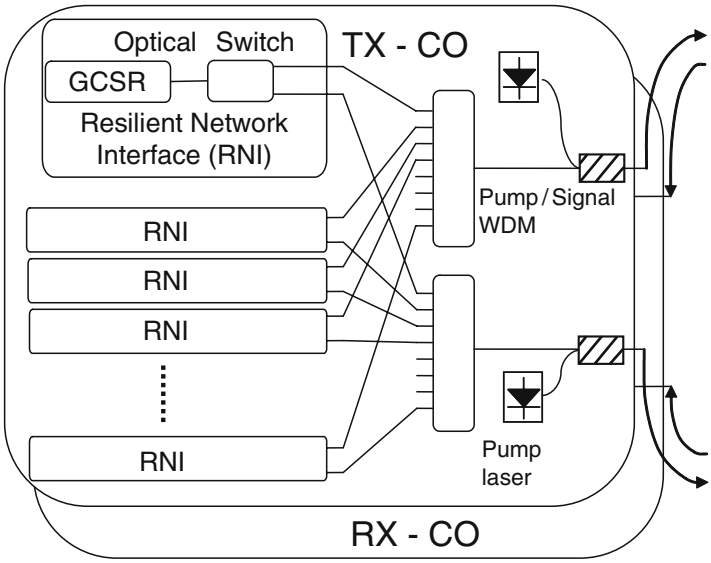

Fig. 7.15 Central Office equipment for double fibre ring Sardana

The CO, shown in Fig. 7.15, uses a stack of tuneable lasers, e.g. Grating-assisted Coupler with Sampled Reflector (GCSR), for serving the different tree network segments on a TDM basis. Tuneable lasers can be shared among different network segments using agile WDM tuning for routing. Downstream and upstream signals are coupled into the corresponding ring fibres by means of the Resilient Network Interface (RNI), which allows for adjustment of the transmission direction by means of Optical Switches (OS). This provides two possible paths to reach each RN, providing always a path to reach all the RNs even in case of fibre failure.

When the network grows and a new set of users has to be added, a new RN can be connected to the WDM Ring, no modification of any other already installed sections is required, and just two wavelengths channels have to be assigned from the CO to the new tree sections.

The RN shown in Fig. 7.16 can perform the add/drop function in a switchless way, simply by broadband X/Y optical couplers (X% of power passing and Y% drops) at the ring, as described in the Single Fibre Ring Sardana or by use of thin-film filters. It is a very mature technology, able to provide very good performances at low cost. The main differences with previous RNs are:

- The RN now drops the RN's assigned wavelengths and is transparent for the rest of WDM signals.
- The drop insertion loss reduces from 10.2 dB to only 0.6–0.8 dB (1.1 dB is specified as maximum). Also the pass insertion loss also reduces from 1.4 to 0.5–0.8 dB (0.25–0.4 dB for each filter).

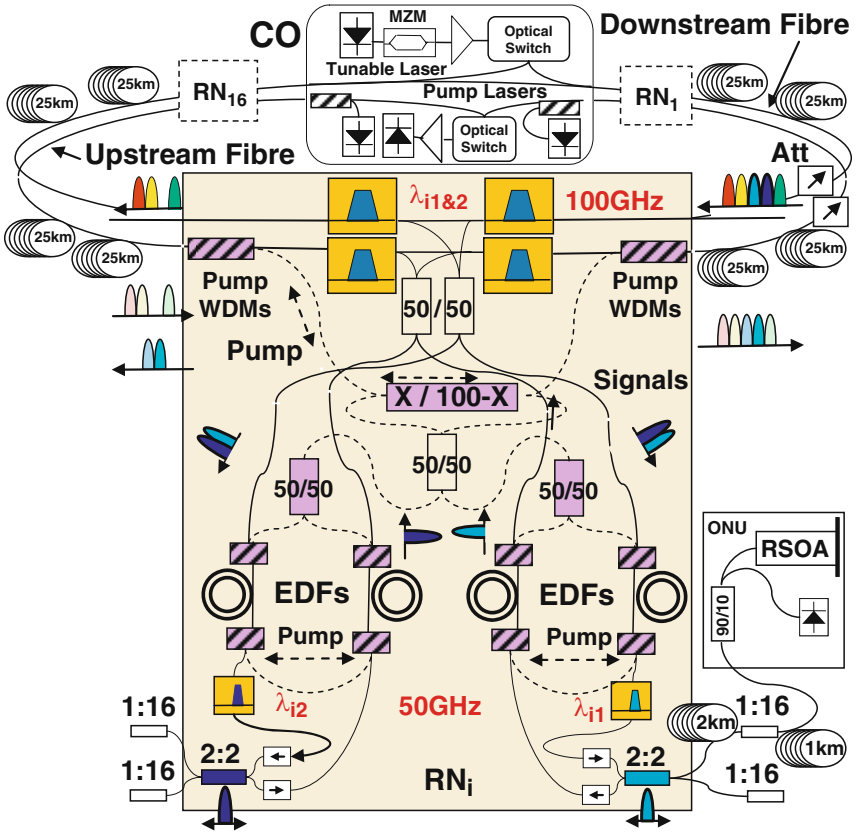

Fig. 7.16 Setup of the Remote Node based on thin-film filters for a splitting ratio of K = 32

After the signal drop, 3 dB power splitters allow to receive and transmit signals in both directions of the ring, implementing the resiliency and traffic balance properties of the Sardana network [Lazaro07a].

In order to achieve an increased power budget, remote amplification is introduced. Optical amplification is performed at the RNs by means of Erbium Doped Fibres (EDFs) , remotely pumped by 1,480 nm lasers which are located at the CO, Fig. 7.15. Two pump lasers are WDM-coupled for bidirectional, balanced pumping and resilience against fibre failure. The pump power levels, propagating through the fibre ring to the RNs, provide some additional Raman amplification. Because of that, the upstream fibre is preferred for pump propagation, as upstream signal power levels are usually weaker than the downstream ones. It can be noticed that the complexity of the network is concentrated at the CO, since its cost is shared among the users of the PON, while the ONUs are kept simple and the external plant fully passive. At the RN, the pump is previously demultiplexed and fed to the EDFs for amplification of up- and downstream of each tree.

At each RN, two single fibre TDM PON trees are connected. Depending on *K*, the bandwidth per user for 16, 32 and 64 users at the tree are respectively 156, 78 and 39 Mbps at 2.5 Gbps in case of network saturation. Because the compatibility of the new extended access network with already standardized protocols is important, we maintain *K* in this range, e.g. *K* = 32 in Fig. 7.16, and increase the number of the user by adding new RNs to the network.

Finally, for a much more convenient network implementation with identical ONUs, we propose wavelength-agnostic transmission devices. Reflective Semiconductor Optical Amplifiers (RSOAs) are suitable devices due to their capabilities for remodulation and amplification, as well as their wavelength independence. With the described network configuration, up to 80 channels covering the C-band with the 50 GHz ITU grid can be used at the WDM ring, leading to a maximum network size of 40 RN and 2,560 served users.

7.3.2.1 Setup and Experimental Results

A test-bed demonstration of the Sardana network has been built up. The downstream modulation format used in our setup is ASK at 10 Gbps, using a Mach-Zehnder modulator (MZM), as shown in Fig. 7.16. It provides a minimum guaranteed bandwidth of about 150 Mbps per user in a half duplex configuration. As a half duplex system, the tuneable laser of the CO is providing an optical carrier for half of the time to the ONUs to allow for intensity modulated (IM) upstream by the RSOAs. Using RSOAs with modulation capabilities up to 2.5 Gbps, a minimum guaranteed upstream bandwidth of about 40 Mbps can be offered to each ONU.

Also a more efficient remote pump distribution scheme has been implemented. A fraction of the remote pump, transmitted from the CO to the RNs, is dropped by the *x*/(100–*x*) splitter and used by the EDF (one for each channel and propagation direction). A second thin-film filter (0.5 dB insertion loss) selects the operative wavelength of each TDM tree and simultaneously performs as an optical filter of the EDF's Amplified Spontaneous Emission (ASE) . For NF reduction of the EDFs, forward pumping configuration is implemented (though not shown in Fig. 7.15 for the upstream EDFs to avoid a too complex figure). The transition from double fibre ring to single fibre tree section is more efficiently implemented by a 2:2 optical coupler together with two isolators. Two 1:16 splitters provide the 1:32 splitting ration. Extra lengths of 2 and 1 km can be used as drop fibres from RNs to the ONUs.

The RN in our setup is implemented using a low doped EDF (HE980) and 200 GHz available filters. At the CO, two 1,480 nm pump lasers for the remote pumping, optical switches for path selection and two Erbium Doped Fibre Amplifiers (EDFAs) as upstream's preamplifier and downstream's booster are used. The 100 km fibre ring is implemented by Single Mode Fibre (SMF) wheels of 25 km. The rest of the RNs are emulated by optical variable attenuators.

The feasibility of the proposed network has been proved for 512 ONUs and 50 km ring, 512 ONUs and 100 km and 1,024 ONUs and 50 km, represented by A,

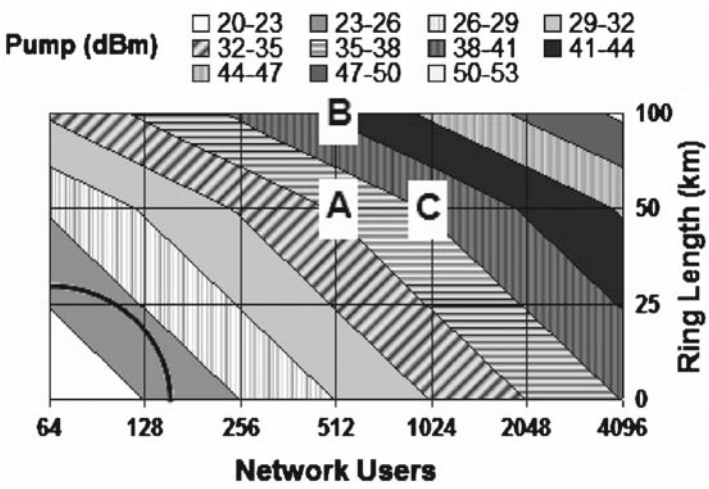

Fig. 7.17 Pump power required and setup conditions

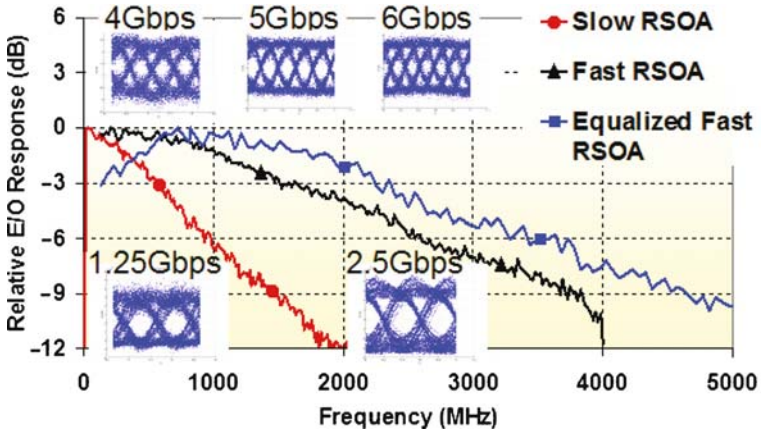

Fig. 7.18 Frequency response at 1,530 nm and –15 dBm input signal power levels and eye diagrams

B and C in Fig. 7.17, respectively. They have been demonstrated by means of BER measurements of the downstream and upstream signals, for the furthest and thus worst RNs of each configuration. They are, in case of non fibre failure: RN4 at 25 km for A, RN4 at 50 km for B and RN8 at 25 km for C. For the analysis of configuration B, the additional 5 km were emulated by optical attenuators.

A faster RSOA can provide high bit rate IM upstream signals at 1.25, 2.5 and 5 Gbps. Figure 7.18 shows the measured E/O bandwidth for a typical response (from a commercial RSOA for comparison), the response curve of the fast RSOA and the broadened curve of the fast RSOA after equalization which was done by

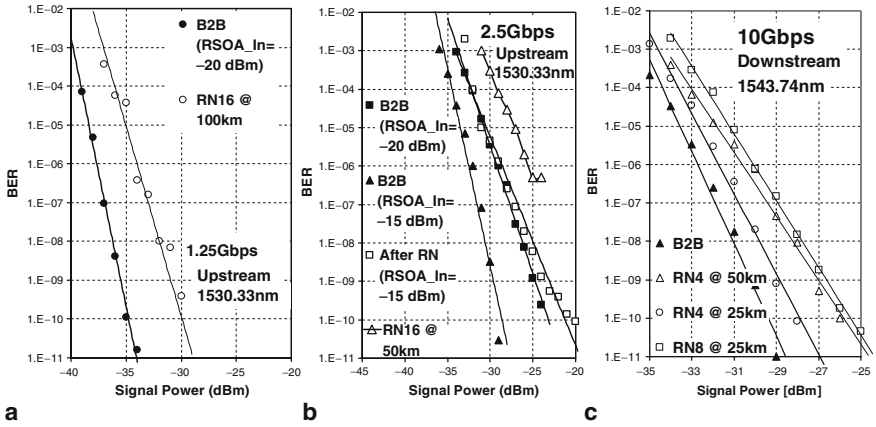

Fig. 7.19 Up- and downstream BER measurements

adapting a passive high frequency filter to the RSOA. Figure 7.18 also includes the eye diagrams obtained at 1.25, 2.5 and 4 Gbps (1,530 nm) as well as 5 and 6 Gbps (1,510 nm).

7.3.2.2 Transmission Experiments

In a previous work, the capabilities of a fast RSOA based on the same technology have been tested to transmit at 2.5 and 5 Gbps [Chanclou07]. The transmission at 2.5 Gbps was possible at a BER of 10^{-9} between 1,488 and 1,520 nm for a WDM PON including the effects of Rayleigh Backscattering (RB) and 20 km attenuation. It is expected that the spectrum of the next samples will shift to 1,530 and 1,560 nm. Besides, the transmission measurements that are shown in Fig. 7.19a have been done at 1,530 nm (for compatibility with the gain profile of a remotely pumped EDF). Figure 7.19a shows that at 1.25 Gbps, 1,024 ONUs (16 RNs) along 100 km can be reached even in the worst conditions of a fibre cut.

For the case of higher bit rates which are provided by using a new fast RSOA, shown in Fig. 7.19b, a number of 1,024 ONUs can be reached. A comparison between third and fourth curve shows that it is not the OSNR reduction but the fibre

Chapter 8
Economic Models

Russell Davey, Jose A. Lazaro, Reynaldo Martínez, Josep Prat, and Raul Sananes

A techno-economical study is performed first for an extended Passive Optical Network (PON) with static Wavelength Division Multiplexing (WDM) upgrade, and second for a more futuristic PON with reflective Optical Network Units (ONUs) and dynamic WDM capability.

8.1 WDM/TDM PON

Technological progress in optical fibre transmission has made enormous capacities in access and metro networks technically possible. There is no *technical* reason why everyone could not have gigabits/s of data to their home using optical access systems which are commercially available today – the obstacles are purely economic. Equally in metro networks, commercially available DWDM (Dense Wavelength Division Multiplexing) equipment could technically deliver approaching 1 Tbps to each and every local exchange or central office, if economics dictated. Today the focus for researchers into optical fibre communications needs therefore to be on cost reduction. Innovation is required to reduce the cost of optical components, but a premise of this document is that a radical new way of thinking is also needed into system and network architectures.

8.1.1 Bandwidth Growth – The Margin Challenge

Network operators around the world are rapidly deploying broadband to residential customers. The intention is that broadband will provide benefits to society as a whole but will also fulfil a vital role for the network operators in compensating for the decline in traditional fixed telephony revenues. By deploying broadband networks, operators are significantly increasing the capacity of their networks, and there is of course an increased cost associated with doing this.

The unit cost of bandwidth has decreased over the years as the underlying technology has advanced and manufacturing volumes have increased. The cost of the underlying

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electronic and optical technologies (lasers, optical fibres, Application-Specific Integrated Circuits ASICs, etc.) is well-known to follow a cost reduction with volume known as a learning curve [Cunningham80]. A learning curve is defined as the percentage decline in the price of a product as the (cumulative) product volume doubles. Technologies typically follow a ~80% learning curve which means that the price of the product at volume 2V will be ~80% of the price at volume V. Since the underlying technologies which we use to build networks follow ~80% learning curves, it should be no surprise that the price of bandwidth has historically followed a similar price reduction (with bandwidth substituted for volume). We can therefore use this historical trend to extrapolate the cost of expanding network capacity to deliver increased bandwidth broadband services.

We now address the revenue generated by this increase in network capacity. From a macroeconomic scale, the gross domestic product of most countries increases only by a few per cent per year. So for a network operator to have a sustained revenue growth of more than a few per cent per year would imply fundamental shifts in consumer spend towards telecoms at the expense of another area of the economy. Looking at things on a microeconomic scale, current worldwide broadband market trends tell us that while consumers will pay for higher speed internet access, the amount they are prepared to pay does not increased in proportion to the amount of bandwidth. Of course increased revenues from broadband must also be offset against declining revenues from traditional telephony. All in all we find that revenues are likely to grow more slowly than costs as bandwidths grow, leading to margin erosion as shown in Fig. 8.1.

To remain economic network operators therefore need to follow a two-pronged strategy. Firstly, they must develop new services which shift consumer expenditure

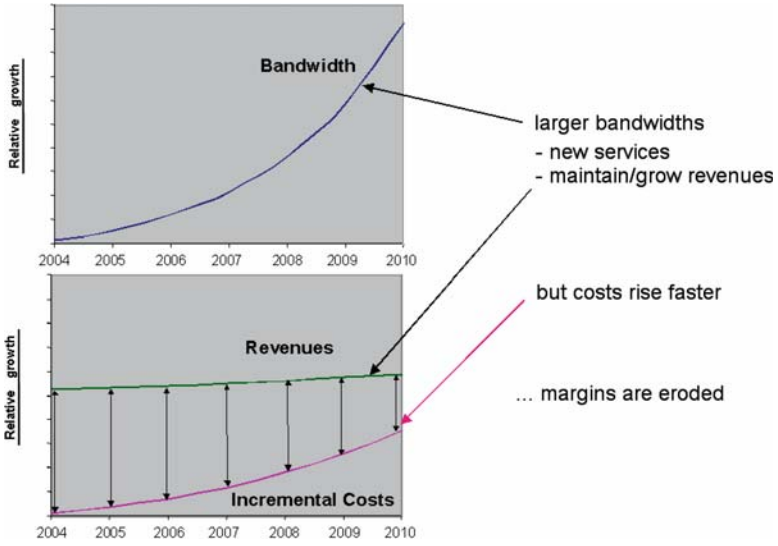

Fig. 8.1 Margins are eroded as bandwidth grows

towards telecoms away from another section of the economy (e.g. travel). This will be challenging. Secondly, they must constantly strive to reduce the cost of bandwidth within their networks.

8.1.2 Economically Sustainable Bandwidth Growth

To remain economic, network operators would like to maintain its return on capital expenditure (ROCE) during a period of growth. This section quantifies the price decline of bandwidth which is necessary to maintain ROCE while growing the network for future broadband services.

If all growth is expressed as a compound annual growth rate (CAGR), it is possible to derive a simple analytical relationship between the growth in revenue (G_R) and the growth in bandwidth (G_B) in order to maintain ROCE.

$$1+G_R \geq (1+G_B)^{1+L} \tag{8.1}$$

where $L = Log(\mathrm{L}\%/100)/Log(2)$

and L% is the learning curve for the price reduction in bandwidth expressed in its traditional form as a percentage. As mentioned previously an 80% learning curve means that the unit price of a product at volume 2V is equal to 80% of the price at volume V.

Figure 8.2 plots G_B against L for contours of constant G_R. We now estimate the rate of growth in bandwidth (G_B) for some future United Kingdom broadband service

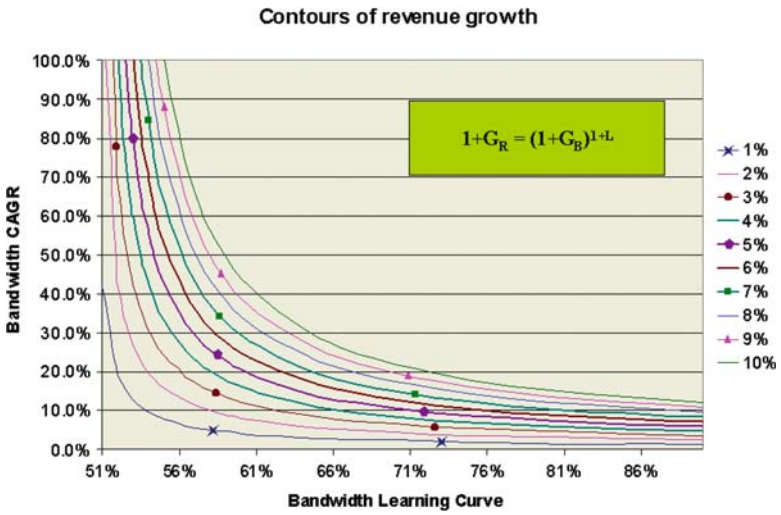

Fig. 8.2 Relationship between economically sustainable revenue growth, bandwidth growth and the price reduction of bandwidth required

scenarios. Note that these are scenarios not forecasts and they apply to the United Kingdom as a whole. We consider three scenarios:

- Conservative internet
- Optimistic internet plus moderate video
- Videocentric

Table 8.1 shows the main service, customer take-up and usage assumptions behind the scenarios. Figure 8.3 shows the ingress traffic to the core network resulting from each of these scenarios.

We can approximate compound annual growth rates for the three service scenarios shown in Fig. 8.3. The results are shown in Table 8.2. If we assume an annual revenue growth of ~5%, we can then obtain the bandwidth learning curve required for each scenario to maintain its ROCE. The results are also shown in Table 8.2.

We see that the conservative internet scenario requires a bandwidth learning curve of ~70% to be economic. This is comparable to the learning curves of the underlying technology (fibres, lasers, electronics) and so should be achievable. However the other two higher bandwidth scenarios require learning curves of ~54% and ~52%. Figure 8.4 shows the learning curves for some well-known technologies and compares them to the ~54% bandwidth learning curve required. No technology has sustainably achieved a ~54% learning curve and so it seems safe to say that the two higher bandwidth scenarios (optimistic internet + moderate video; videocentric) will not be met. Referring to Fig. 8.2 we see that even an optimistic revenue growth of ~10% per year would not materially change this conclusion.

Table 8.1 Service scenario assumptions

	Conservative internet		Optimistic + moderate video		Video centric	
	2009/10	2014/15	2009/10	2014/15	2009/10	2014/15
Total broadband Internet customers (millions) (includes cable modem)	9.4	12.3	10.7	14.8	10.9	16.2
Number of VDSL/Fibre customers (millions)	0	0	1.65	2.9	2.1	7.7
Video/VoD customers (millions)	0.14	0.54	1.5	3.5	2.0	8.7
Average Internet session time/day (mins)	75	80	96	107	101	126
Average Internet session Bandwidth (kb/s)	77	114	320	1,270	488	4,780
Average Video session time/day (mins)	24	24	58	70	94	128
Average Video session Bandwidth (kb/s)	2,000	2,000	7,000	7,500	7,280	7,400

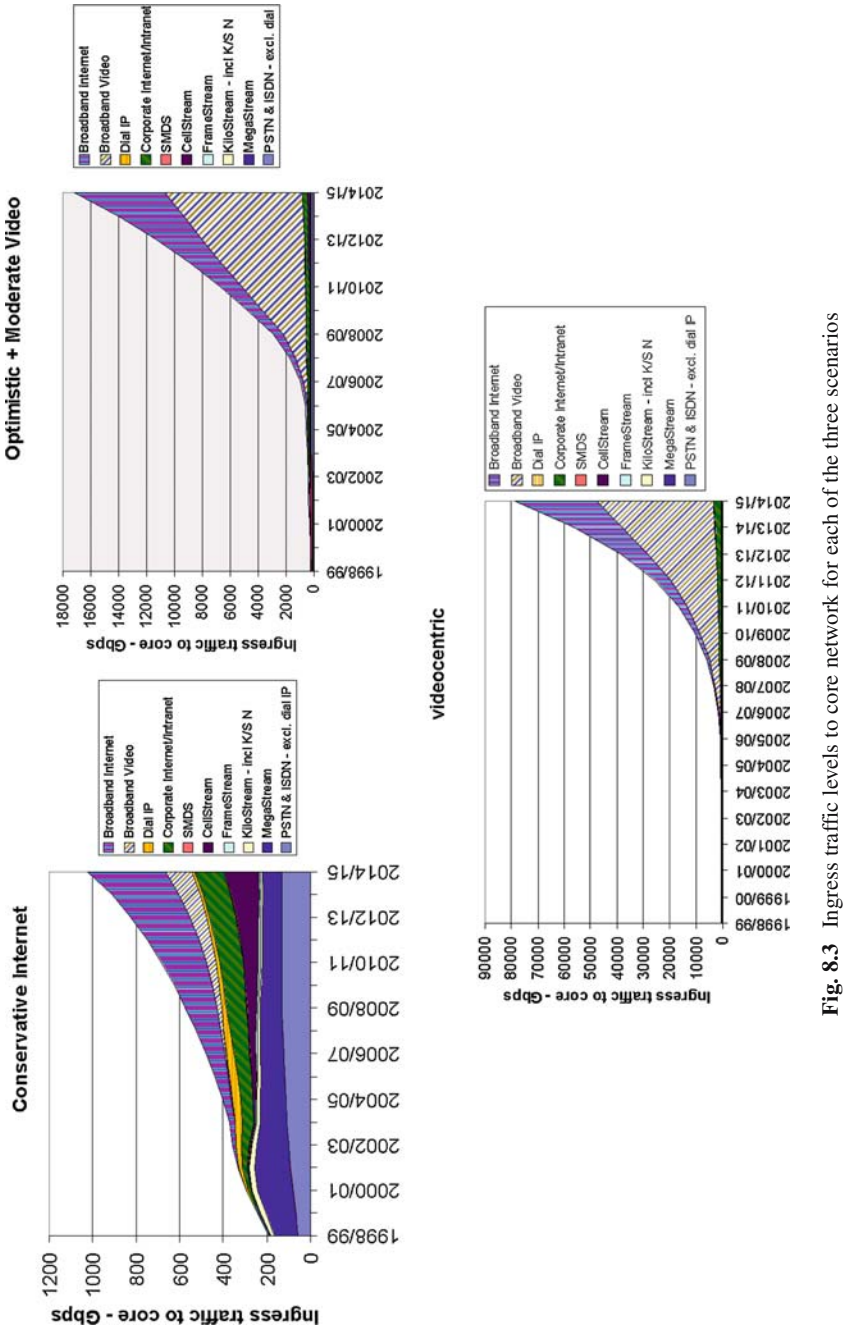

Fig. 8.3 Ingress traffic levels to core network for each of the three scenarios

Table 8.2 Bandwidth growth rates for each service scenario and the bandwidth learning curve (price decline) required to maintain the return on capital expenditure (assumed 5% per year revenue growth)

Scenario	Bandwidth growth CAGR fit (%)	Bandwidth learning curve (%)
Conservative internet	12	~70
Optimistic internet plus moderate video	50	~54
Videocentric	80	~52

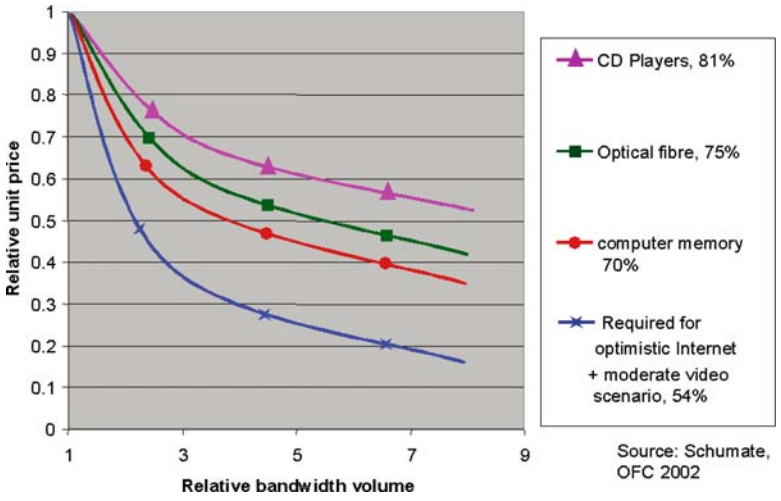

Fig. 8.4 Bandwidth learning curve required for our optimistic internet + moderate video scenario compared to the learning curves of some common technologies

8.1.3 The Need for a New Network Architecture

In the previous section we have seen that optimistic but realistic future service scenarios can result in traffic growth in excess of 50% per year. To economically sustain such a growth it would be required that the price of bandwidth reduces with volume at a rate which has not been sustainably achieved by any technology. So how can we economically sustain such a high growth in bandwidth? Since the underlying components (fibres, lasers, etc.) cannot price decline at the required rate the only answer is that we must reduce the amount of equipment in the network. We must reduce the number of interfaces between boxes, reduce the number of boxes in the nodes and even reduce the number of nodes in the network. In short we must simplify the network. We need a new network architecture enabled by a new generation of optical systems. The long reaches made possible by optical technology are a key enabler for the new architecture.

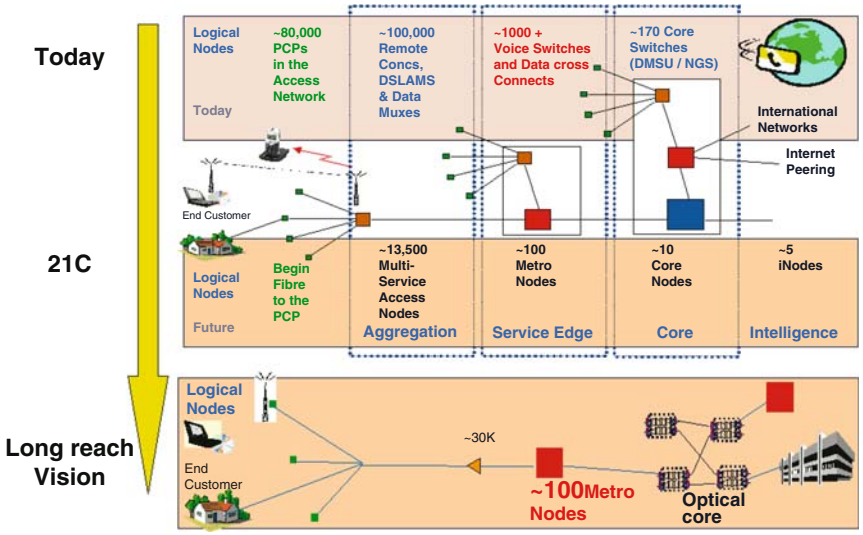

Fig. 8.5 Simplifying the British Telecom network from today to the 21st century (21C) network and then to the long reach access vision

Figure 8.5 uses the evolution of the British Telecom network to illustrate an example of an evolution to a simpler network architecture. The top row in Fig. 8.5 represents the British Telecom network today. The middle row represents how British Telecom's announced 21st century network initiative will simplify the network – reducing the number of interfaces and boxes. In the 21st century network there are ~100 major metro nodes. These are connected to the customer via an aggregation network tier containing ~13,500 multi-service access devices (MSANs) , which are connected to the customers via the access network and an via an intermediate network tier.

The bottom row in Fig. 8.5 shows a longer term further evolutionary step which simplifies the network still further. We refer to this as the long reach vision and it contains two components:

- Customers are directly connected to the ~100 metro nodes by long reach passive optical networks.
- The metro nodes are interconnected by a wavelength granularity intelligent optical core network [Lord05].
- In this document we focus on the long reach access component.

8.2 Long Reach PONs

The system architecture of a Long Reach PON (LR-PON) is shown in Fig. 8.6. The head-end of the LR-PON, known as the Optical Line Terminal (OLT) is located in the metro node. Since all transmitters are in the 1,550 nm window, erbium doped fibre

amplifiers are used at the head-end and at intermediate local exchange location(s) to extend the reach to at least 100 km. The 100 km reach is required to allow dual parenting of local exchanges onto metro nodes. In order to make efficient use of fibre the target split is 1:1024. In order to give high bandwidths per customer the target bit rate in both upstream and downstream directions is 10 Gbps.

Note that the architecture shown in Fig. 8.6 does not require the optical amplifiers to be gated. Also note that LR-PONs should not only be thought of as for fibre-to-the-home applications. They could equally be used to feed VDSL cabinets (e.g. with Gigabit Ethernet) or radio base-stations and as such provide a flexible, future-proof solution.

As mentioned above, one of our objectives is to reduce the amount of equipment in nodes. Figure 8.7 shows how this is achieved for a typical British Telecom local exchange (Ipswich, serving fifteen thousand customers). The 21st century network reduces the space and power significantly compared to today. LR-PONs would then improve the situation still further to just a single rack of erbium doped fibre amplifiers, consuming just 100 W of electrical power.

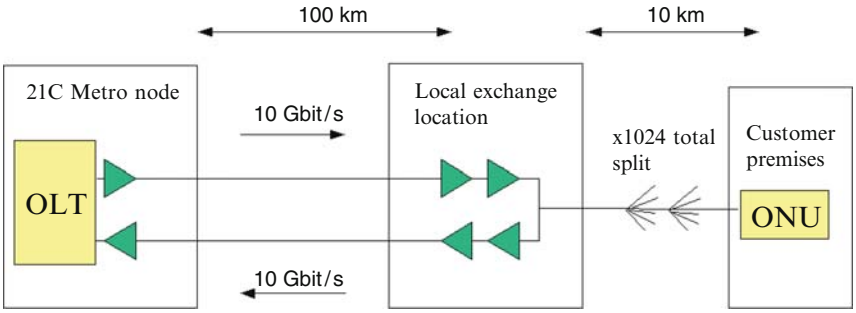

Fig. 8.6 Long reach PON system architecture (triangles are erbium doped fibre amplifiers)

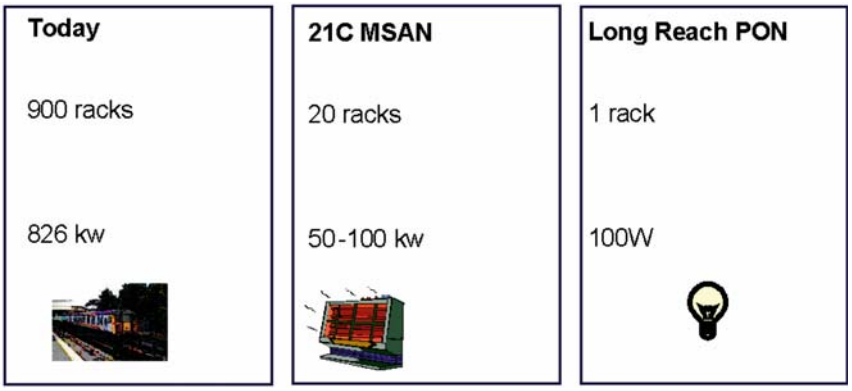

Fig. 8.7 Power consumption comparison

8.2.1 Long Reach PON – Technical Challenges

LR-PONs are not commercially available and are as yet a research concept. Nevertheless the potential benefits they offer are such that they are a very worthy research topic. Given the large span losses involved, the first question one asks is whether adequate signal to noise performance can be achieved. This has been shown to be the case for continuous bit-streams where error-free performance has been reported [Nesset05] using a commercially available XFP transceiver and forward error correction. The second question one asks is whether the various PON protocols will scale to long lengths and high split. It has been experimentally proven that long lengths in themselves are not an issue for existing Gigabit Passive Optical Network (GPON) systems [Davey05]. A question which remains to be answered is the impact on system performance of "bursty" upstream data passing through erbium doped fibre amplifiers. Further work is also needed to develop a suitable 10 Gbps burst-mode receiver for the LR-PON head-end. Cost reduction of the ONU transmitter is clearly another key area.

In order to further improve fibre efficiency, it would be attractive if WDM could be used on the portion of the LR-PON between the metro node and local exchange [Davey05]. Early results have been reported where this is achieved without the use of transponders at the local exchange yet with "colourless ONUs" [Talli05].

In order to economically support significant bandwidth growth, it is necessary to simplify networks. In the longer term, the concept of long reach access promises to provide further network simplification and so cost reduction. First steps in demonstrating the feasibility of the long reach access concept have been reported.

8.3 Long Term Dynamic WDM/TDM-PON Cost Comparison

For an economic analysis of PON architectures we propose five different networks for evaluation. These networks include several techniques as power splitting, bidirectional fibre transmission, and WDM for static and dynamic wavelength assignment. For this, we developed some mathematical models for the cost of these networks and compared them using a medium density metropolitan area as a reference. The cost was referred to the bandwidth per user in order to have a fair way of comparing the performance and at the same time the cost of the networks. The first three scenarios are for reference purposes as they are not WDM networks, but are very interesting to focus the cost comparison.

- "P2P (Point-to-Point) – 2 fibres Network": As seen in Fig. 8.8, it has two fibres for every connection, which gives the complete bandwidth of the network for every direction.
- "P2P – single fibre Network": It is also a P2P architecture but with only a single fibre between the OLT and the ONU [Prat02]. It is shown in Fig. 8.9. It uses two different wavelength lasers for downlink and uplink directions in order to eliminate the Rayleigh backscattering effect.

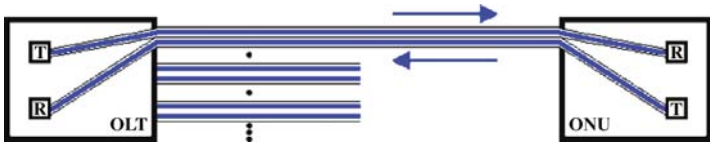

Fig. 8.8 Point-to-Point – 2 fibres Network

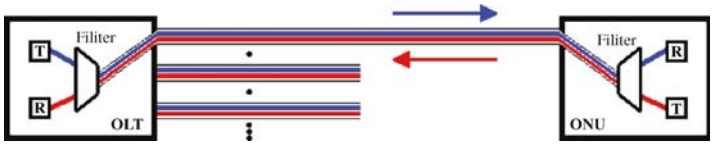

Fig. 8.9 Point-to-Point – single fibre Network

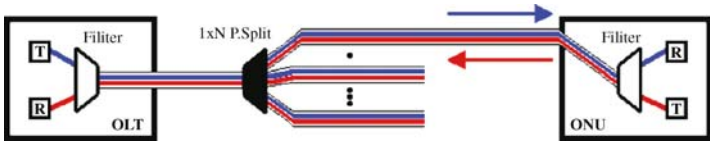

Fig. 8.10 Single fibre PS-PON

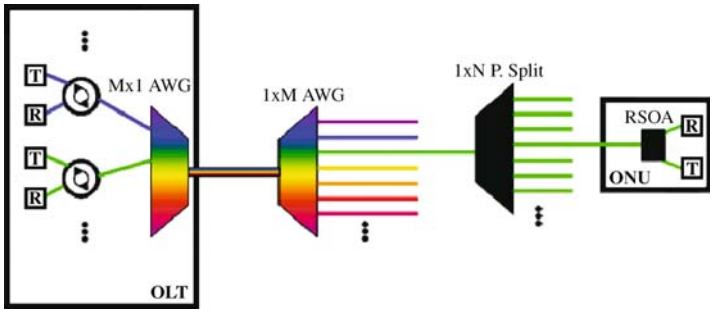

Fig. 8.11 CWDM-PS-PON with reflective Optical Network Unit

- "Single fibre Power Splitter – PON (PS-PON)": It is shown in Fig. 8.10. It is a classical PON in which all ONUs receive the same optical signal, therefore multiplexing users transmissions in time.
- "CWDM (Coarse Wavelength Division Multiplexed) – PS-PON with reflective ONU": It uses M Distributed Feedback (DFB) lasers in the OLT to address through the Arrayed Waveguide Grating (AWG) a specific power splitter, creating a virtual PS-PON for every wavelength (Fig. 8.11). In the Remote Node a Reflective Semiconductor Optical Amplifier (RSOA) remodulates the optical carrier for the upstream direction [Arellano05ofc].

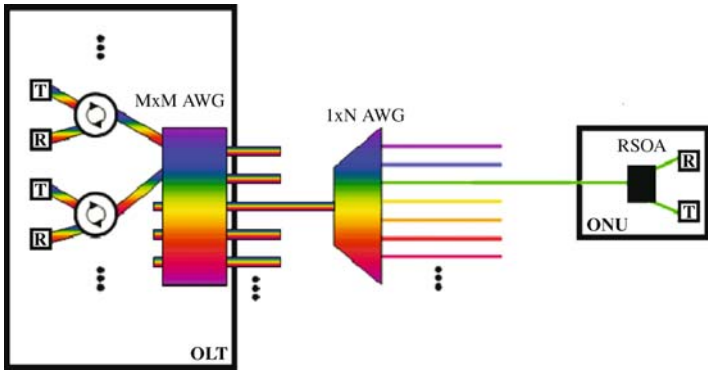

Fig. 8.12 Multi-Free Spectral Range Dynamic WDM PON with reflective Optical Network Unit

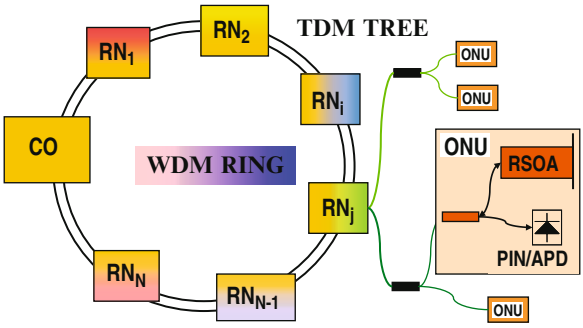

Fig. 8.13 Resilient WDM/TDM PON with reflective Optical Network Unit

- "Multi-FSR (Free Spectral Range) Dynamic WDM PON with reflective ONU" uses tuneable lasers in the OLT to select the output port of the M × M AWG in the OLT as well as the 1 × N AWG output port, which connects to a single ONU, where data is sent [Bock04] (Fig. 8.12). This architecture uses the Latin Routing characteristic of the AWG in order to have more flexibility when transmitting information to different users.
- "Resilient WDM/TDM PON with reflective ONU": as an example of a ring plus trees topology, providing basic resiliency and intended for a high density of users using a reduced number of fibres (>1,000 users/2 fibres), long reach (100 km), using a fully passive outside plant and single-fibre colourless access, as the Sardana network described in Chapter 7 (Fig. 8.13).

Table 8.3 shows the optical components used in each network and the available bandwidth per user. Here, we considered for the TDM networks the theoretical bandwidth per user limit, which is having all users connected and transmitting and receiving with the maximum available bandwidth.

We obtained the equations for the Capital Expenditures (CAPEX) of each one of the five different networks, serving N users. We considered only the optical components in the network. Then we normalized the cost off all components against the price of a Fabry-perot laser. The equation for the complete network cost is:

$$CAPEX_{network} = OLT + MUX + N \cdot ONU + Feeder + Distribution + Splices \quad (8.2)$$

The price of fibre cables, both in the feeder and in the distribution sections are calculated using a model that represents how the cost per fibre of the cables decreases as the number of fibres in the cable increases.

This is:

$$FO = \left(A + B \cdot N + C \cdot N^2\right) \cdot L = \alpha(N) \cdot L \quad (8.3)$$

FO stands for the price of the fibre optic cable and L represents the length of the cable. α is the function that approximates the cost of the cables depending on the number of fibres (N). A, B and C are constants that represent different parts of the fibre cost:

- A represents a fix cost of a fibre cable that is mainly the enclosure.
- B represents the cost of each fibre.
- C represents a drop in the relative cost of the cable as N increases.

Table 8.3 Optical components and available bandwidths per Optical Network Unit in each network

Network	OLT equipment for N users	Outside plant multiplexing	ONU equipment	Bit rate per ONU (down-up)
P2P–2 fibres Network	N.1,350 nm laser N.receivers	–	1,350 nm laser Receiver	R – R
P2P – single fibre Network	N.1,550 nm laser N.receivers N.filters	–	1,350 nm laser Receiver Filter	R – R
Single fibre PS-PON	1,550 nm laser Receiver Filter	Power Splitter	1,350 nm laser Receiver Filter	R/N – R/N
CWDM – PS-PON	DFB laser Receiver Circulator Mx1 AWG (/M)	CWDM AWG P. Splitter	Optical filter RSOA	R/N – R/N
Multi-FSR WDM PON	Tuneable laser Receiver Circulator M × M AWG	DWDM AWG	Optical filter RSOA	R/N – R/N
Resilient WDM and TDM PON	DFB laser Mx1 AWG Optical Switch or Interleaver (for resilience)	Remote Node	RSOA	R/N – R/N

In Table 8.3 we present the cost of the different parts of the network. These costs are calculated for a network with N users and are obtained considering the components shown in Table 8.4.

OLT Equipment includes lasers, photo receivers, circulators, if needed, and for the "Multi-FSR WDM PON with reflective ONU" the price of the M × M AWG. Outside plant multiplexing is composed by the Power-Splitters and AWG that each network uses for multiplexing-demultiplexing. ONU Equipment includes lasers, receivers, circulators and RSOAs depending on the case. Feeder and distribution consider only the cost of FO cables. For the splices, one splice is used for each component connected to one fibre. There is also at least one splice in the outside plant.

These costs have been obtained by averaging the costs of several vendors.

With the given formulas and taking the respective values for each variable, we obtained the total cost of the cabling of these networks in an urban area in the city of Barcelona, Spain following some certain cabling models that are shown in Fig. 8.14 [Sananes05].

Table 8.4 Cost of Optical Line Terminal, outside plant, Optical Network Unit, fibre and splices cost for different network architectures

Network	OLT equipment	Outside plant multiplexing	ONU equipment	Feeder	Distribution	Splices
P2P – 2 fibres Network	2·N	0	2	$\alpha(2N)\cdot L_f$	$\alpha(2)\cdot L_d\cdot N$	0.6·N
P2P – single fibre Network	5·N	0	4	$\alpha(N)\cdot L_f$	$\alpha(1)\cdot L_d\cdot N$	0.3·N
Single fibre PS-PON	5	0.1·N	4	$\alpha(1)\cdot L_f$	$\alpha(1)\cdot L_d\cdot N$	0.2 + 0.2·N
CWDM – PS-PON	7	0.3 + 0.1·N	5	$\alpha(1)\cdot L_f$	$\alpha(1)\cdot L_d\cdot N$	0.2/M + 0.2 + 0.2·N
Multi-FSR WDM PON	12	0.6·N	5	$\alpha(1)\cdot L_f$	$\alpha(1)\cdot L_d\cdot N$	0.2 + 0.2·N
Resilient WDM/TDM PON	3	0.3·N	3	$\alpha(2)\cdot L_f$	$\alpha(1)\cdot L_d\cdot N$	0.2 + 0.2·N

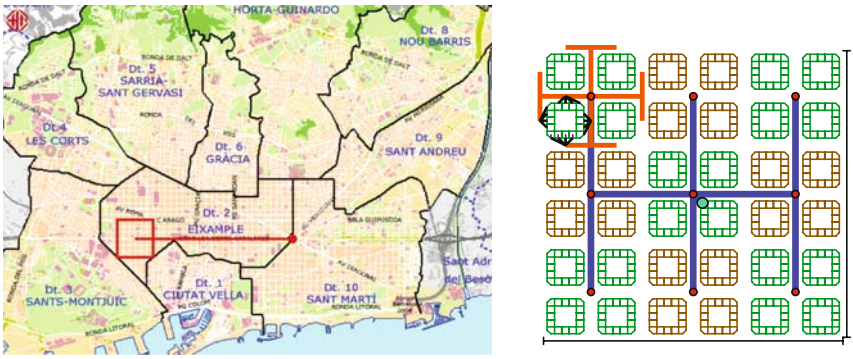

Fig. 8.14 (a) Barcelona and the considered cabled area, (b) cabling model used in the calculations

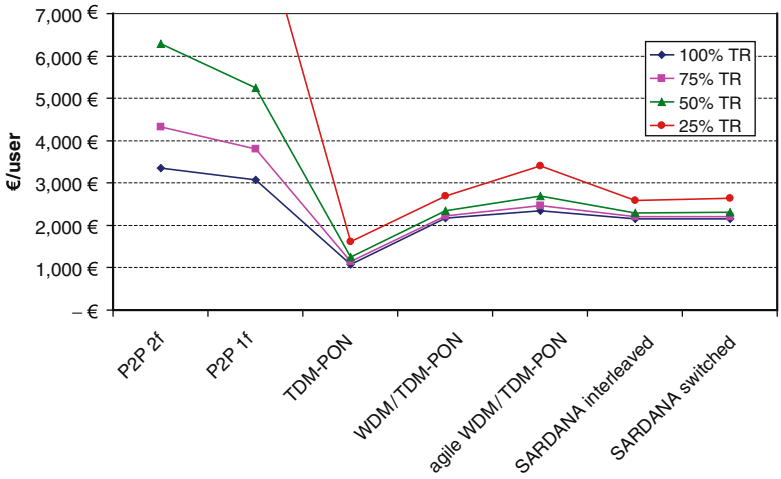

Fig. 8.15 Capital Expenditures per user with current prices for different take rates

Figure 8.15 shows the total cost per user of each one of the studied networks with the obtained current prices for different take rates, where the installation and digging costs are not included in the calculations.

It can be seen in Fig. 8.15 that the point-to-point solutions are not able to deliver services in a cost effective way. In fact, the cost of the P2P approach is eight times the total cost of the P2M (Point-to-Multipoint) approach [Sananes04] for some cases. This is due to the huge amount of fibre that is needed for this architecture. It can be seen in Table 8.4 that the total cost of cabling scales directly with the number of users, because the P2P architectures require at least one fibre from each ONU up to the OLT.

Much more efficiently, the P2M architectures arrive to the served area with a single fibre from the OLT and the segregation in one fibre per user is performed near the clients, reducing the cabling cost in that way.

It is also important to notice in Fig. 8.15 that with current prices, the TDM PON is the most adequate solution in terms of the CAPEX for deploying a FTTH system. It is even a more cost effective solution than the resilient WDM/TDM PON architecture proposed in Chapter 7 (Sardana).

But while the already standardized TDM PONs are currently in deployment as the first step in all optical access networks, next generation PONs (ngPONs) as the resilient WDM/TDM PON architecture offers characteristics as higher user density, extended reach, flexibility, scalability, resiliency – characteristics, that would be mandatory for the future user demands and which can not be achieved with TDM PON architectures.

On the other hand, it should be noticed that the cost of ngPONs can be even lower than the one of pure TDM PONs due to the evolution of components. This will provide a cost effective migration path to advanced optical networks, like the DWDM PON.

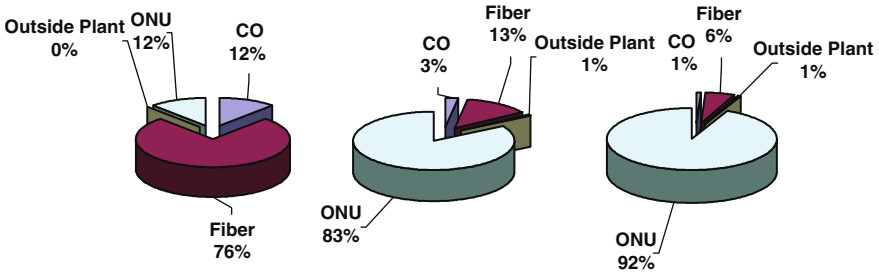

Fig. 8.16 Contribution to the total cost by each part of the network. Left: Point-to-Point Network, center: TDM PON Network, right: resilient WDM/TDM PON

The reason for this future decrease of ngPONs is based on the fact that, as it can be seen in the cost breakdown analysis shown in Fig. 8.16, while 76% of the cost of P2P networks is due to fibre infrastructure, for the case of the resilient WDM/TDM ngPON, 92% of the total cost of the network is due to the ONU, which is a RSOA as explained in Chapter 3.

We have to consider two important aspects. The first one is that the cost of optical networks has decreased over the years as the underlying technology has advanced and manufacturing volumes have increased. It is well known that the cost of the underlying electronic and optical technologies as lasers, optical fibres, ASICs, etc. follows a cost reduction with volume known as "learning curve". A learning curve is defined as the percentage decline in the price of a product as the (cumulative) product volume doubles. Technologies typically follow an approximately 80% learning curve which means that the price of the product at volume 2V will be about 80% of the price at volume V [Prat06]. The second one is just to remember the important tendency curve for semiconductors, a law that has been in the literature for more than 40 years, called the Moore's Law [Schaller97].

By combining those two ideas, it would not be risky to expect that the prices of the components based in semiconductors will follow a similar learning curve, and therefore the access technologies based on semiconductors will follow a cost reduction as well.

Due to that, it should be no surprise that the prices of Sardana and the other networks topologies that employ components which follow the learning curves explained, might get down.

It would be a huge mistake to expect that the total cost of the P2P solution, for example, will be reduced following the mentioned learning curve. That is, as shown in Fig. 8.16, because most of its cost is due to the huge economical inversion in optical fibre cabling (≈76%), and we can not assume that the price of the optical fibre is guided by Moore's Law.

We can therefore use this historical learning curve and extrapolate the prices of the components which are affected by those curves. Figure 8.17 shows the total cost of each one of the network topologies considered, changing through time.

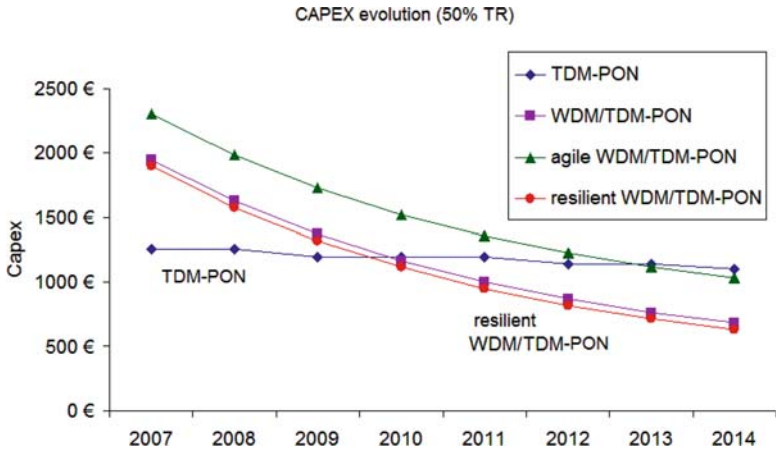

Fig. 8.17 Expected prices for network topologies considered in the study for the next decade (take rate = 50%)

Due to the different contributions to the total cost shown in Fig. 8.16, not all the CAPEX experience a reduction in the same way. This is because not all the network architectures that are considered have the same amount of components affected by the learning curve (semiconductors). In fact, as it can be seen from Fig. 8.17, the PS-PON topology price barely varies through time. Nevertheless, the resilient WDM/TDM ngPON architecture, having a total cost which is constituted in 92% by a semiconductor device, is the most affected architecture in the cost, and it is the first that beats the TDM PON topology in terms of CAPEX, having in addition the properties of capacity, speed, user density, scalability, resiliency and flexibility that allow this architecture to fulfil the future user demands.

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